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GEOLOGY OF CENTRAL KANSAS UPLIFT[1]

EDWARD A. KOESTER[2]
Wichita, Kansas

ABSTRACT

The Central Kansas uplift is a buried, oft-rejuvenated structural feature trending northwest and southeast across west-central Kansas which has been revealed by drilling for oil and gas within the past 10 years. It originated in pre-Cambrian time as a series of parallel batholiths and persisted as a positive element throughout much of Paleozoic time. Several periods of broad warping and erosion occurred during the Paleozoic and Mesozoic eras. Folding normal to the axis of the uplift has occurred principally in early Pennsylvanian and post-Cretaceous time and has been an important factor in the local accumulation of petroleum. The geologic history of the Central Kansas uplift is very similar to that of the Ozarks of Missouri.

INTRODUCTION

The Central Kansas uplift occupies an area in central Kansas and probably part of south-central Nebraska, whose present northwestward trending structure has been developed by several periods of warping and truncation, the earliest of which dates back to pre-Cambrian time. Subsequent movements of variable magnitude, and covering different portions of the geographic area, have slightly altered the original size and shape of the uplift. Warping on a broad scale in northwest and southeast directions, which has recurred throughout Paleozoic and Mesozoic time, has been modified by depositional thinning toward the northwest of some of the Paleozoic systems and by folding in approximately northeast and southwest directions along old existing lines of weakness. Warping has occurred chiefly in post-Algonkian (?), post-Canadian, post-Hunton, early Pennsylvanian,

[1] Manuscript received, July 11, 1935.

[2] Geologist, Darby Petroleum Corporation.

post-Missouri, and post-Cretaceous time. Depositional thinning toward the north and west has affected mainly Cambro-Ordovician and Pennsylvanian strata. Most of the northeast-southwest folding occurred in early Pennsylvanian and post-Cretaceous time.

The complete structural history of the Central Kansas uplift cannot be written now. Knowledge of it dates only from the discovery of commercial oil production in Russell County in November, 1923. Several years elapsed before sufficient stratigraphic and structural information could be gleaned from drilled wells to enable geologists to understand the true size, shape, and importance of this feature. Since information concerning it is increasing and will continue to increase as long as deep tests are drilled in the area, this paper should be considered a progress report.

It is the intention of the writer to review the contributions of previous workers, to discuss briefly the ideas expressed in their publications, and to show how the conception of a major warped area has grown in the minds of Mid-Continent geologists.

A description of the stratigraphy of the uplift must include mention of the sediments found in the bordering basins. Mention of the structure of the uplift entails a review of the structural features around it. An examination of them affords a means of interpreting the structural history of Kansas.

Acknowledgments.—The writer acknowledges the assistance of the many Kansas geologists with whom he has discussed the data embodied in this paper, but special mention should be made of the contributions of L. C. Morgan, J. I. Daniels, and Anthony Folger to an appreciation of this problem. The writer is indebted to C. J. Stafford for assistance in the preparation of the illustrations accompanying the paper and to Marvin Lee and A. R. Meyer for criticising the manuscript.

PREVIOUS STUDIES

Rubey and Bass[3] in 1925 published a valuable contribution to the geology of west-central Kansas in their bulletin on Russell County. In the same publication, Bramlette[4] gave a subsurface correlation of stratigraphic units from Russell County to Marion County, and Moore[5] published his studies on a fauna from wells in central Kansas and correlated the upper part of the oil-producing "Oswald lime" in the Fairport field with the Oread limestone of the Douglas group.

[3] W. W. Rubey and N. W. Bass, "The Geology of Russell County, Kansas," *Geol. Survey of Kansas Bull. 10* (1925).

[4] M. N. Bramlette, *ibid.*, Pt. 2, pp. 87–93.

[5] R. C. Moore, *ibid.*, Pt. 3, p 71, pp. 94–105.

Moore also mentioned the existence of an important unconformity at the base of the Pennsylvanian.

Bass[6] in 1926 described the geology of Ellis County and remarked that the pre-Pennsylvanian unconformity existed throughout an area of several counties.

The occurrence of Ordovician sediments in western Kansas has been mentioned by Udden,[7] who gave a list of Ordovician fossils recovered in cuttings from a Russell County well, and by Twenhofel,[8] who showed that Ordovician rocks underlie a large area in western Kansas.

Denison,[9] in a brief discussion, was the first to mention in print the existence of a broad structural feature in western Kansas which we now call the Central Kansas uplift. He referred to it as a

> large Ordovician land mass to the west and northwest of the Welch well, which has been demonstrated by the numerous wells drilled following the Russell oil discovery. There is here a large area, the limits of which are as yet undefined, where Ordovician is encountered directly beneath Pennsylvanian beds, with a large part of the Pennsylvanian which should correspond to the Cherokee of eastern Kansas missing.

Denison considered this feature, which he referred to as the Russell arch, of Pennsylvanian age, and compared it with the Nemaha Granite ridge of eastern Kansas. The term Russell arch has not been used by later authors.

In the only comprehensive paper yet published on the structural features of central Kansas, Barwick,[10] in 1928, named several of them. He mentioned chiefly the stratigraphy and structure of the Salina basin of north-central Kansas, but also suggested the name Chautauqua arch for the pre-Mississippian extension of the Ozark uplift along the Kansas-Oklahoma line. He further said

> The name Barton Arch is here suggested for the broad pre-Pennsylvanian and probably in part pre-Mississippian high in Ellsworth, Rice, Barton, Russell and nearby counties.

Neither Barwick nor any other geologist in Kansas could realize the full significance of the broad and oft-rejuvenated structural fea-

[6] N. W. Bass, "Geologic Investigations in Western Kansas, Pt. 1, Geology of Ellis County," *Geol. Survey of Kansas Bull. 11* (1926), pp. 11–52.

[7] J. A. Udden, "Occurrence of Ordovician Sediments in Western Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10, No. 6 (June, 1926), pp. 634–35.

[8] W. H. Twenhofel, "Ordovician Strata in Deep Wells in Western Central Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 1 (January, 1927), pp. 49–55.

[9] A. R. Denison, "Discussion of Early Pennsylvanian Sediments West of the Nemaha Granite Ridge," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10 (June, 1926), p. 636.

[10] J. S. Barwick, "The Salina Basin of North Central Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 12 (February, 1928), pp. 177–89.

ture which is now known as the Central Kansas uplift because at that time too little information was at hand concerning the subsurface stratigraphy and structure of the area. Inasmuch as Barwick's definition of the Barton arch is inadequate to describe the structural feature to which he referred, and since that feature is a very different type of structure from what he conceived at that time, the term Central Kansas uplift was used by Morgan,[11] who defined it as

> that area of truncated Mississippian, together with the surrounding area in Central and Western Kansas, . . . whose present form is believed to be caused by Caledonian folding or emergence in a direction parallel to the pre-Cambrian grain followed by Appalachian or Hercynian folding normal to the grain.

The term Central Kansas uplift had been in use among Kansas geologists before Morgan delivered his paper on it before the meeting of the Third Annual Field Conference of the Kansas Geological Society at Lead, South Dakota, on September 4, 1929, but it has been only in the past 2 years that it has been more commonly used in the literature than the abandoned term Barton arch.

Edson,[12] in 1929, described the pre-Mississippian formations from wells drilled in parts of central Kansas and discussed their correlation with the section found at the surface in Oklahoma and the upper Mississippi Valley, but did not discuss in detail the structural significance of the unconformities involved.

McClellan,[13] in 1930, presented a map showing the areal distribution of pre-Mississippian rocks in Kansas and Oklahoma, but unfortunately used subsurface terminology advocated by Barwick, which had never enjoyed common usage among Kansas geologists. In discussing the structure of central and western Kansas, he proposed the name Dodge City basin for a "basin in the southwestern part of Kansas." He also mentioned that

> The real structural backbone of Kansas is a much larger and broader feature, the Chautauqua-Barton Arch, which extends from the Ozark Uplift in a northwesterly direction through Chautauqua, Barton and Norton counties.

In discussing the geological history of the state, he failed to mention the relation of the arched area to the pre-Cambrian grain, which had first been pointed out by Morgan.

[11] L. C. Morgan, "Central Kansas Uplift," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16 (May, 1932), p. 483.

[12] F. C. Edson, "Pre-Mississippian Sediments in Central Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 5 (May, 1929), pp. 441–58.

[13] Hugh W. McClellan, "Subsurface Distribution of Pre-Mississippian Rocks of Kansas and Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 12 (December, 1930), pp. 1535–56.

Rich,[14] in a series of three papers, presented data to support the hypothesis that the oil of Kansas was generated, during the Appalachian revolution, in the deep geosynclinal basins of southern Oklahoma and has migrated northward through certain porous carrier beds, notably the sands of the Simpson formation and the weathered upper portion of the Arbuckle limestone, and accumulated under the control of the structural and geological conditions existing at that time—before the more recent westward tilting of the region.

His papers met with severe criticism from some geologists. His proposal of the name Central Kansas arch for the combined structural unit of the Chautauqua arch, the Central Kansas uplift and the unnamed saddle between them was opposed as confusing. He also proposed the name North Kansas basin for that area in northern Kansas at the close of the Devonian that was later separated into the Salina basin and the Forest City basin by the early Pennsylvanian uplift of the Nemaha Granite ridge.

STRATIGRAPHY

CRETACEOUS

Except for a thin mantle of Quaternary and Tertiary material, all of the outcropping rocks of the area of the Central Kansas uplift are of Cretaceous age, belonging to the Colorado and Dakota groups. They have been adequately described in the more recent publications of the Kansas Geological Survey.

Colorado strata are divided into the Smoky Hill chalk, the Fort Hays limestone, and the Carlile, Greenhorn, and Graneros formations. Each of these has subdivisions which are suitable for mapping surface structure. This has been done by numerous geologists and the surface structure of the area has been carefully worked out. Due to erosion the beds of the Colorado group vary in thickness from the amount shown in Figure 1.

The Dakota group, consisting principally of sandstone and shale, crops out along the major streams in this area and occupies a considerable area on the eastern fringe of the uplift. It is less suitable for structural mapping than the formations of the Colorado group. The Dakota underlies the Graneros shale everywhere and overlies a bevelled surface of Permian Red-beds. Strata of Lower Cretaceous (Commanche) age are included with the Dakota group in this paper.

[14] John L. Rich, "Function of Carrier Beds in Long-Distance Migration of Oil," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15 (August, 1931), pp. 911–24; "Source and Date of Accumulation of Oil in Granite Ridge Pools of Kansas and Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15 (December, 1931), pp. 1431–52; "Distribution of Oil Pools in Kansas in Relation to Pre-Mississippian Structure and Areal Geology," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17 (July, 1933), pp. 793–815.

PERMIAN

Permian rocks in this area may be conveniently divided into an upper Red-bed section, the Cimarron series, and a lower, less red, more calcareous section, the Big Blue series. The 800 or less feet of

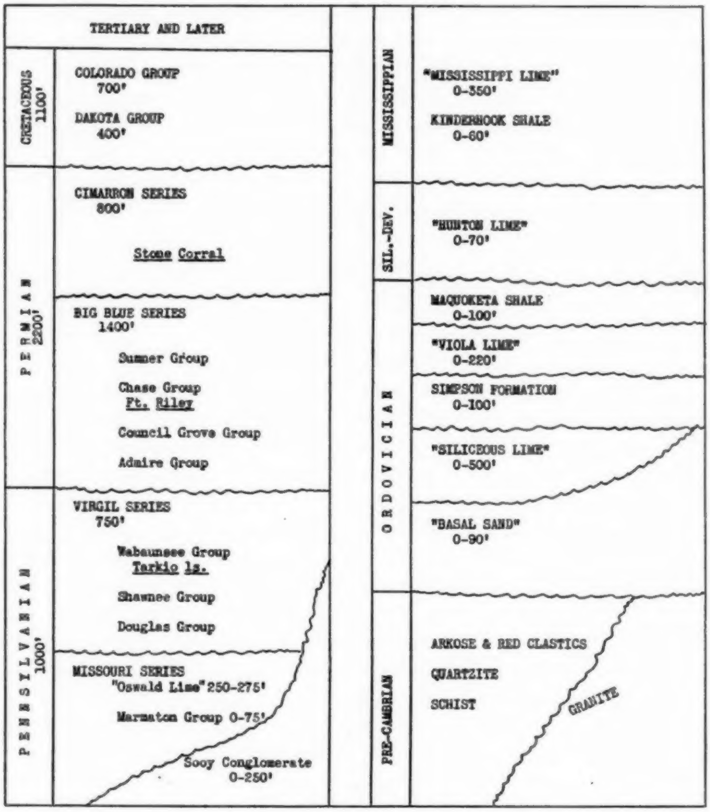

FIG. 1.—Stratigraphic section of Central Kansas uplift.

beds constituting the Cimarron series consist of red sandstone, shale, and siltstone, with a minor amount of anhydrite and dolomite. One anhydrite-dolomite member, about 40 feet thick in Russell and Barton counties but thinner toward the east, is an excellent subsurface and core drill marker and has recently been named the Stone Corral

member by Norton.[15] It occurs in the lower part of the Cimarron series.

The Big Blue series contains some very important red shale members, but it lacks the massive red units that are found in the Cimarron. There is also much more dolomite, considerable limestone, a thick salt sequence, and much blue and gray shale. Many minor units of very little thickness can be traced for great distances, as sedimentation in the Chase, Council Grove, and Admire groups was evidently uniform over large areas. These units can be identified in well samples and correlations of some of the more prominent subsurface markers, such as the top of the Fort Riley limestone, the top of the Neva limestone, and the base of the Americus limestone, can be made from drillers' logs.

The thicknesses (Fig. 1) of 800 feet for the Cimarron group and 1,400 feet for the Big Blue group apply to much of the nuclear area in Russell County.

PENNSYLVANIAN

The Permo-Pennsylvanian boundary is now placed by R. C. Moore at the base of the Indian Cave sandstone member of the Towle shale of the Admire group and the top of the Brownville limestone of the Wabaunsee group. Although this horizon can not always be identified in the subsurface section, its position can be approximately determined. A conveniently used marker is the top of the Tarkio limestone which ordinarily can be picked out in well logs and samples a variable interval below the top of the Wabaunsee group.

Pennsylvanian beds on the nucleus of the uplift are about 1,000 feet thick, but on the flanks are considerably thicker. There is a regional thinning of Pennsylvanian beds toward the west and northwest.

The Wabaunsee group in the Central Kansas uplift area is commonly a series of micaceous sandy shale, relatively thin limestone beds, and important red shale zones. It contrasts somewhat with the underlying Shawnee formation and its members, which are mostly limestone with minor amounts of gray shale. Individual members may be correlated directly with the outcrop sections, as has been done by Kellett.[16]

[15] George H. Norton, "Upper Wellington and Lower Red-Bed Section in Kansas." Paper read by title, Wichita, Kansas, Meeting, Amer. Assoc. Petrol. Geol., March 21, 1935.

[16] Betty Kellett, "Geologic Cross Section from Western Missouri to Western Kansas," prepared for Sixth Annual Field Conference of the Kansas Geological Society, October, 1932.

The westward thinning of the underlying Douglas group is also well shown in Kellett's cross section. The Douglas group is represented in much of the uplift area by less than 100 feet of varicolored shale, usually micaceous and sandy. On many of the local structures and in much of northwestern Kansas, it consists of but 10–15 feet of red and brown shale.

An important unconformity separates the Virgil series from the Missouri series in the Kansas surface section and it can also be found in the subsurface throughout most of Kansas. Probably no beds equivalent to the Peedee group are represented in west-central Kansas, so that the unconformity at the base of the Douglas group overlies Missouri strata that are referred to as the Oswald limestone.[17] The name is derived from the farm name of the discovery oil well of western Kansas, and has been widely used. The top of the Oswald limestone probably represents a horizon in the Lansing group, but, due to erosion, it is not the same horizon at all places.

The Oswald limestone has a maximum thickness of about 275 feet on the flanks of the uplift, where it is underlain by beds probably of Marmaton age. The Oswald is thinner on local "highs" where it overlies pre-Pennsylvanian rocks. In the Gorham field 238 feet of Oswald limestone overlies granite in one well.

The Oswald limestone is composed of alternating limestone and shale, the latter being minor in total amount and occurring in thin "breaks" in the sequence. The most characteristic feature of the Oswald limestone, and one which may be used to distinguish it from other parts of the Pennsylvanian subsurface section, is the oölitic nature of many of its members. Certain oölitic zones may be traced for great distances from field to field, and in general are regular in occurrence, although irregular locally. Nearly all of the oil production from the Oswald limestone has been found in these oölitic zones. However, one well in a pool may miss an oölitic zone, and likewise miss production, although its offset is a profitable producer from the same depth. Certain more or less cherty zones may also be identified. Fossils are not abundant in samples of the Oswald limestone, but zones of ostracods and fusulinids are of assistance in correlating individual units of the section. Some of the shale "breaks" in the Oswald are irregular and local, but a few may be followed over most of the uplift area. Insoluble residues are not necessary in subdividing the Oswald limestone and have not been used. Sand is conspicuous by its absence, except in wells located on sharp local structures overlying

[17] The name, Oswald limestone, refers to the formation commonly known as the "Oswald lime."

buried hills. Here, as in the Gorham pool, the basal portion of the Oswald limestone locally rests directly on pre-Cambrian rocks, and is increasingly sandy in the lower few feet. It also contains fragments of reworked pre-Cambrian quartzite and Ordovician oölitic and dolocastic chert.

Producing zones within the Oswald limestone are generally named from the distance they occur below the top of the "lime," as the 30-foot "pay," the 75-foot "pay," et cetera. However, a "pay" occurring 75 feet below the top of the Oswald limestone in one pool is not necessarily correlative with a "pay" 75 feet below the top in another pool, inasmuch as the top of the Oswald limestone is not of the same age throughout the area. Post-Missouri erosion has removed more of the Oswald beds in some areas than in others.

The Oswald limestone is the time equivalent of the Lansing, Kansas City, and Bronson groups of the eastern Kansas surface section.

Wells located structurally low or on the flanks of the uplift encounter a variable thickness of shale and limestone below the Oswald limestone, which is probably correlated correctly as Marmaton in age. These beds rarely exceed 75 feet in thickness.

Below the Oswald limestone or below the Marmaton beds, and extending to the base of the Pennsylvanian section, is a stratigraphic unit which has been called the Pennsylvanian basal conglomerate, but to which Edson[18] has given the name "Sooy conglomerate." The latter name is derived from the name of one of the first wells drilled in western Kansas, in Barton County. The Sooy conglomerate is a transgressive deposit, overlying rocks from pre-Cambrian to Mississippian in age, and underlying beds ranging in age from Cherokee in central Kansas to possible Permian in northwestern Kansas. In its most common development it is a coarse, cherty, partly sandy conglomerate, commonly cemented with red shale. In many samples the red shale composes most of the material. The chert is commonly white, yellow, red, brown, gray, or black, partly oölitic and dolocastic, rarely sandy, but everywhere weathered and reworked. Dolomite, green shale, gray shale, and other types of pre-Pennsylvanian and Pennsylvanian material are intermixed. Sand grains are fine-to-very coarse, etched, pitted, and frosted. The conglomerate is clearly derived from whatever type of sediments were at hand for reworking and redepositing as the first Pennsylvanian sea advanced upon the uplift. It represents the first deposit of a transgressive sea. Locally

[18] F. C. Edson, "The 'Sooy' Conglomerate of Kansas," *Tulsa Geol. Soc. Digest* (1934), pp. 30–32.

it contains several sand zones, within the coarser cherty material. Naturally the thickest sections of it are found in structural or topographic depressions.

The Gorham sand is a near-shore phase of the Sooy conglomerate. Its name is derived from the Gorham field, where it was first found productive of oil in commercial quantities. The Gorham sand has also been found productive at other localities in Russell, Barton, and Rush counties. It varies in character locally, depending on the environment of its deposition. It may be a pure, well sorted sand in one well, an arkose in an offset well, and a somewhat tightly cemented dolomitic sandstone in another offset. It has been found overlying pre-Cambrian granite, pre-Cambrian quartzite, the "Siliceous lime," and an Ordovician conglomerate.

Some geologists believe the Gorham sand in the Gorham field and elsewhere is the basal sand of the Paleozoic section and of Cambro-Ordovician or Cambrian age. The writer does not endorse this view for several reasons. The Gorham sand is definitely reworked. In the Gorham field the fine texture of the Gorham sand contrasts sharply with the coarse, spherical grains so common to the basal sand. In other areas the Gorham sand contains coarse grains with rounded edges which are not spherical but ellipsoidal in shape, clearly reworked basal sand material. In still other areas the Gorham sand contains reworked material derived from the "speckled quartzite" of pre-Cambrian age, which is not common to the basal sand. The Gorham sand, being a near-shore phase of the basal Pennsylvanian conglomerate, naturally varies considerably from place to place, whereas the basal sand is relatively uniform in character. Finally, the Gorham sand, overlying the "Siliceous lime" as it does in some wells in the Gorham and Beaver pools, can not be Cambrian in age. Locally the material of the Gorham sand is clearly derived from the "basal sand" of the Paleozoic section, which has been reworked by the encroaching Pennsylvanian sea.

MISSISSIPPIAN

Rocks of Mississippian age have been removed by post-Morrow pre-Atoka erosion from the nucleus of the uplift and part of its flanks. However, they occur in places on its flanks and in the neighboring basins. The thicker representation is the well known "Mississippi lime" which probably correlates with the Boone limestone of the Ozark region. Chester sediments, which are found in southwestern Kansas, do not occur near the higher parts of the uplift. The "Mississippi lime" is normally a white, gray, or buff, sucrose, cherty lime-

stone or dolomitic limestone with a thickness of more than 250 feet in Lincoln county. Below it occurs the Kinderhook shale, up to 60 feet in thickness, which is normally light gray-to-black, and contains the spore, ***Sporangites huronensis***.

SILURO-DEVONIAN

Unconformably below the Mississippian in the Salina basin lies a section of dolomite and dolomitic limestone which has been referred

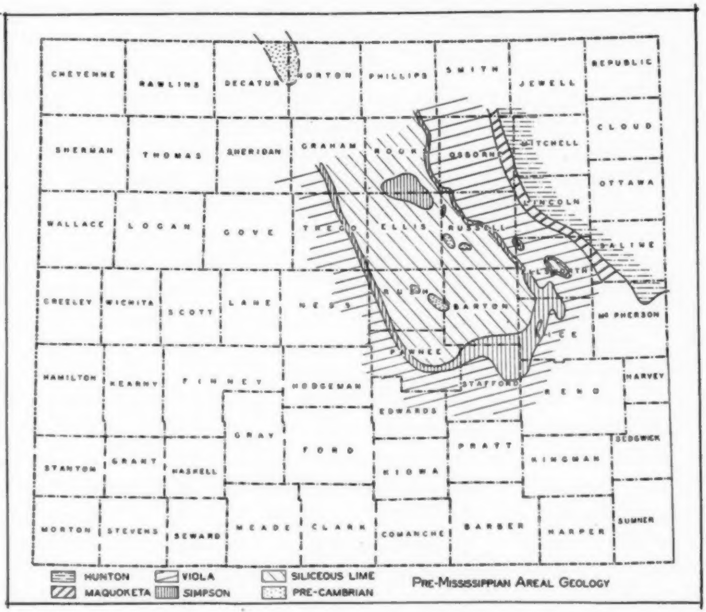

FIG. 2.—Pre-Mississippian areal geology of west-central Kansas. (March, 1935.)

to as "Hunton limestone." Much discussion has arisen concerning the age of this subsurface unit and the question has not been settled, but it appears to occupy approximately that part of the stratigraphic column covered by the Hunton limestone of Oklahoma. The southern limit of the Salina basin "Hunton" is shown on Figure 2. A discussion of its age and the age of a similar looking dolomite in an outlier in Sedgwick, Harvey, McPherson, Reno, and Rice counties is not pertinent to this paper, other than to mention that pre-Kinderhook erosion has removed the "Hunton limestone" from a large part of Kansas, including all of the nucleus of the uplift.

ORDOVICIAN

Maquoketa.—The uppermost Ordovician formation found in central Kansas is a light greenish gray, splintery shale, in part dolomitic or grading into dolomite, about 70 feet in maximum thickness, which is correlated very closely with the Maquoketa shale of Iowa and the Sylvan shale of Oklahoma. The term Maquoketa is in most common use for this unit.

"Viola lime."—Underlying the Maquoketa shale is a series of limestone and dolomite which is here referred to as "Viola lime." The name is a field term to describe beds which may be conveniently grouped together and which occupy the approximate position of the Viola limestone and adjacent strata of the Oklahoma section. Barwick called this series the Urschel limestone, but his term never was widely used. The "Viola lime" of common Kansas usage includes beds correlative with post-Viola, Fernvale-Viola, and Galena strata. The white crystalline (Fernvale) phase can be traced through a large portion of western Kansas, and is present on the north side of the uplift in central and eastern Russell County. On the southwest flank more than 200 feet of "Viola lime" occurs, but here it is mostly a cherty dolomite. Careful subsurface sample work will eventually determine the age and occurrence of the units included in the term.

Simpson formation.—Underlying the "Viola lime" on the flanks of the uplift are beds of fossiliferous green shale and minor amounts of sandstone and limestone which have been correlated with the upper Black River-Spechts Ferry shale of Iowa. Their normal thickness is about 60 feet. These beds were formerly referred to as Decorah, but the Spechts Ferry member is now considered the upper member of the Platteville limestone rather than the lower member of the Decorah formation.[19] They are equivalent to the upper part of the Simpson of Oklahoma. Older Simpson beds occur in the southernmost part of Kansas. Simpson beds are missing over the higher part of the uplift, which is here called the nucleus, except for an inlier in southern Rooks County and northern Ellis County.

"Siliceous lime."—In describing the pre-Pennsylvanian stratigraphy of the northern Mid-Continent region, Aurin, Clark, and Trager[20] used the term "Ordovician Siliceous lime" to describe a series of thick dolomite, limestone and sandstone which underlies various subsurface units ranging in age from Mississippian to Ordovi-

[19] G. Marshall Kay, "Ordovician System in the Upper Mississippi Valley," *Kansas Geol. Soc. Guidebook Ninth Annual Field Conference* (1935), pp. 281–95.

[20] F. L. Aurin, G. C. Clark, and Earl A. Trager, "Notes on the Subsurface Pre-Pennsylvanian Stratigraphy of the Northern Mid-Continent Oil Fields," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 5, No. 2 (March-April, 1921), pp. 117–53.

cian and which overlies pre-Cambrian rocks wherever found. They included in the term a basal sand sequence which normally occurs between the dolomite and pre-Cambrian rocks. Inasmuch as the dolomitic portion of the "Siliceous lime" in this area is similar lithologically to a part of the Arbuckle group of Oklahoma and the sand portion is somewhat similar to the Reagan sand, some geologists use these terms for the units which are here referred to as "Siliceous lime" and "basal sand." There is much more reason to correlate the "Siliceous lime" in any part of Kansas with the Cambrian and Ordovician sequence of the Missouri Ozarks, which have been carefully subdivided, than with the Arbuckle group of Oklahoma, about which relatively little has been published.

Examination of samples from wells west of the Ozarks have definitely shown that the unconformities which are known in the Ozarks occur in western Missouri and eastern Kansas. These unconformities occur between Cambrian and Ozarkian (pre-Potosi), within the Ozarkian (pre-Proctor and pre-Gunter), between Ozarkian and Canadian (pre-Roubidoux), and there are several minor breaks within the Canadian. In a Chautauqua County well, McQueen[21] has found a basal sandy, arkosic phase of the Eminence overlying the Bonneterre dolomite, with the Potosi, Derby-Doe Run, and Davis missing. This represents the Cambrian-Ozarkian break. The Middle Ozarkian unconformity is shown by the absence of the Proctor between the Eminence and the Gunter. In the Canadian, the Cotter overlies the Roubidoux sandstone with no Jefferson City dolomite intervening. In Butler County, Van Buren dolomite (Ozarkian) overlies pre-Cambrian rocks. Other information from McQueen and other geologists supports the view that as one follows the "Siliceous lime" westward from the Ozark region the lower portions of the section are missing so that younger deposits overlap, and rest on pre-Cambrian rocks. The upper portion of the "Siliceous lime" in the Voshell field of McPherson County has been identified as Cotter. Lerke[22] and others have found Cotter and Jefferson City beds in the upper portion of the "Siliceous lime" in wells within the nuclear area of the uplift where the "Siliceous lime" is much thinner than on the flanks. Ozarkian beds have been found under Canadian and above pre-Cambrian in a deep well in Barber County by McQueen.[23] It appears that there is no Cambrian in Kansas except in the southeastern corner of the state and that the

[21] H. S. McQueen, letter of March 8, 1935.

[22] Boris V. Lerke, oral communication.

[23] H. S. McQueen, *op. cit.*

"Siliceous lime" on the nucleus of the Central Kansas uplift and a good part of its flanks is Canadian in age.

"*Basal sand*."—The "basal sand," which nearly everywhere underlies the "Siliceous lime" in Kansas, is interpreted as a transgressive deposit of varying age. In southeastern Kansas it locally may be directly equivalent to the Lamotte sandstone. Farther west it rises in the section and is Ozarkian. In wells close to or on the uplift it is clearly Canadian or upper Ozarkian. Its correlation on the uplift with the Reagan or Lamotte is therefore untenable. It is important that in the higher wells it is thinner than in lower wells. Several wells have found as little as 10–20 feet of it, whereas its thickest section, which may be excessive due to poor samples, is 90 feet. Normally the basal sand is about 60 feet thick. White[24] has mentioned that the basal sand is missing over "Ozark Island" in the southwestern Ozark region of northeastern Oklahoma. The same condition is found locally in central Kansas, notably in the Breford pool, T. 17 S., R. 10 W., where the "Siliceous lime," probably of upper Canadian age, rests directly on pre-Cambrian quartzite.

On the Central Kansas uplift, the "basal sand" is normally a coarse, well rounded-to-spherical, poorly indurated sandstone, which is drilled easily. It contains a relatively large percentage of very coarse, frosted, spherical grains, which are commonly not pitted or etched. There is also much medium-to-fine, frosted sand.

PRE-CAMBRIAN

The basement rocks of Kansas are granite, schist, quartzite, arkose, and red clastics. Their character and distribution have been described by Morgan.[25]

PRE-MISSISSIPPIAN AREAL GEOLOGY

Figure 2 depicts the structural growth of the Central Kansas uplift up to the beginning of Mississippian time. However, over much of the central part of the uplift, Mississippian beds are absent, hence for that area the pre-Mississippian areal map also represents pre-Pennsylvanian areal geology. This applies to that area inside the U-shaped band of Simpson outcrop which may be referred to as the nucleus of the uplift. Here the Oswald limestone or the Sooy conglomerate rests directly on "Siliceous lime" or earlier rocks, except for the Simpson

[24] Luther H. White, "The Subsurface Distribution and Correlation of the Pre-Chattanooga ('Wilcox' Sand) Series of Northeastern Oklahoma," *Oklahoma Geol. Survey Bull. 40-B* (June, 1926), p. 10.

[25] L. C. Morgan, "Pre-Cambrian Studies in Central Kansas," paper presented before the Association at the Wichita meeting, March 21, 1935.

inlier in southern Rooks and northern Ellis counties, which, incidentally, may cover a larger area than shown.

Within the nucleus are two somewhat narrow bands, marked by the outcrop of pre-Cambrian rocks, which may be called the "Russell rib" and the "Rush rib." These are true structural "highs" in the Ordovician and pre-Ordovician rocks, as well as being topographic monadnocks. The Russell rib extends in a northwest direction from southwestern Ellsworth County across southern Russell County to the vicinity of Gorham, whence it curves more northward through the Fairport oil field, thence northwestward across a small part of Ellis County into Rooks County. From southeastern Barton County the Rush rib trends northwestward to the northwestern part of Rush County, whence it turns slightly northward through western Ellis County and eastern Trego County into Graham County. The northern limits of these two ribs have not been found and their eastern extensions are less definitely known. However the effect of the warping which caused the Russell rib is apparent in the Geneseo pool of north-central Rice County, where Pennsylvanian rests on a very thin section of Simpson. The widening of the Simpson band of outcrop in northeastern Stafford County is evidently a reflection of the Rush rib.

The broad area in Pawnee County in which the "Siliceous lime" underlies the Pennsylvanian represents a third rib running approximately parallel with the other two. Due to lack of control, not much is known about this Pawnee rib. Its location was first suggested in 1930 by the discovery of granite at a relatively shallow depth in a well in central Pawnee County.

Two high areas of "Siliceous lime" cropped out in early Pennsylvanian time northeast of the nucleus of the uplift, one in central Ellsworth County near Ellsworth, the other at Wilson on the Russell-Ellsworth County line. They represent a line of pre-Mississippian warping which can be traced northwestward from the Burns dome in northern Butler County through the Peabody, Ritz-Canton, and McPherson fields. While this tectonic feature, for which the name Wilson-Burns element is here proposed, is closely related to the Central Kansas uplift, at least in part, in age and alignment, it does not seem to be a part of that structure.

From the southwestern portion of Rice County to the vicinity of Ellsworth extends a relatively steep fold to which the name Ellsworth anticline has been given.[26] Its position can be approximately found on the pre-Mississippian area map (Fig. 2) by the north-south Simpson

[26] Edward A. Koester, "Development of the Oil and Gas Resources of Kansas in 1931 and 1932," *Geol. Survey of Kansas Min. Res. Cir. 3* (1934) p. 51.

band of outcrop in this area.[27] The Chase, Ploog, and Lorraine pools are on this axis. This is an early Pennsylvanian fold which has been formed at the front of the southeastward plunging Central Kansas uplift. Its position suggests that the uplift had acted as a buttress repelling a force from the southeast, possibly from the Ozarks. It appears that this force, transmitted through the basement complex, was released by the folding of younger beds over a zone of weakness in the older rocks, possibly pre-Cambrian fault zones.

The "Siliceous lime" and the basal sand are unusually thin in all wells on each of the ribs and these beds are absent in several areas, so that the Pennsylvanian Oswald limestone rests directly on pre-Cambrian granite, schist, or quartzite with little or no basal conglomerate. There is also undeniable evidence of overlap relationships between the "Siliceous lime" and basal sand. The latter is ordinarily thinner on the top of a rib and in at least one instance a thin section of "Siliceous lime" rests directly on pre-Cambrian quartzite with no intervening basal sand.

As the pre-Cambrian area in Norton and Decatur counties is based on control from only one well near Norcatur, it may be much smaller or larger than indicated. However, wells in Nebraska along the Cambridge anticline have found pre-Cambrian underlying the Permian or upper Pennsylvanian, so it seems there may be a broad area in northern Kansas with little or no pre-Pennsylvanian sediments. The Norcatur "high" apparently is a continuation of the Rush rib.

There appears good evidence of a saddle between the Russell and Rush ribs in Ellis County, but the definite identification of a saddle of any magnitude in Barton and Rush counties awaits further control.

The periods of warping to which the uplift was subjected varied in size and scope. That the post-Devonian uplift was broad is proved by the fact that, though the Hunton band of outcrop in the Salina basin is fairly near the nucleus of the uplift, there is no known Hunton on the southwest side of the feature in southwestern Kansas. The closest Hunton is in northwestern Oklahoma.

The illustrations of Morgan[28] have given some hint as to the pre-Ordovician structural history of the uplift. Figure 2 presents a picture of its configuration at the beginning of Mississippian time, and in part at the beginning of Pennsylvanian time. More may be learned concerning it from a study of succeeding maps.

[27] The illustrations accompanying this paper were completed March 20, 1935. Subsequent drilling has shown them to be slightly in error, but the writer does not consider the recent information to be important enough to warrant re-drafting.

[28] L. C. Morgan, *op. cit.*

STRUCTURAL AND ISOPACH MAPS

The attitude of the top of the "Siliceous lime" with reference to our present sea-level, as shown in Figure 3, shows the plunge of the uplift toward the southeast and its north and south flanks. The ribs are less well shown on the contour interval used, but are well brought out in a map of smaller contour interval. Due to southward tilting the Rush rib is at present 200–250 feet lower than the Russell rib on sea-level datum. The lowest part of the Salina basin from a structural standpoint is demonstrated by the contours in Mitchell County. The low area west of the McPherson anticline, or Voshell trend, here named the Conway syncline, is evident in western McPherson County and northeastern Reno County. On the southwest side of the uplift the Ordovician beds dip relatively steeply across Edward, Kiowa, Ford, and Clark counties toward the Anadarko basin.

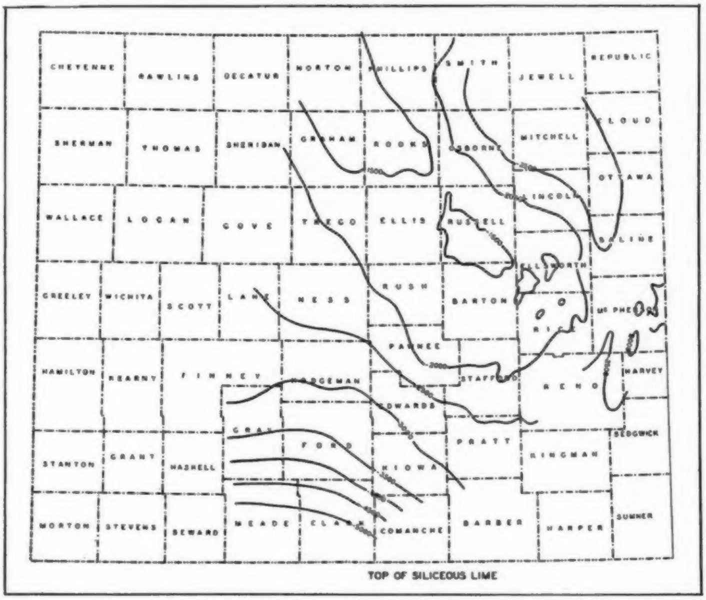

FIG. 3.—Generalized structural contour map of top of "Siliceous lime." Contour interval, 100 feet. (March, 1935.)

It is not the writer's intention to show the details of local structure. Many of the irregularities caused by several periods of folding between

the end of the Ordovician and the present are not shown. However, the northeast-southwest folding of early Pennsylvanian time (Wichita disturbance) and of post-Cretaceous time (Laramide revolution) is illustrated by the projecting contours in northwestern Russell County along the axis of the Fairport anticline, in Rice and Stafford counties, and along the McPherson anticline in McPherson, Harvey, and Reno counties. This narrow folding, with some faulting, contrasts sharply

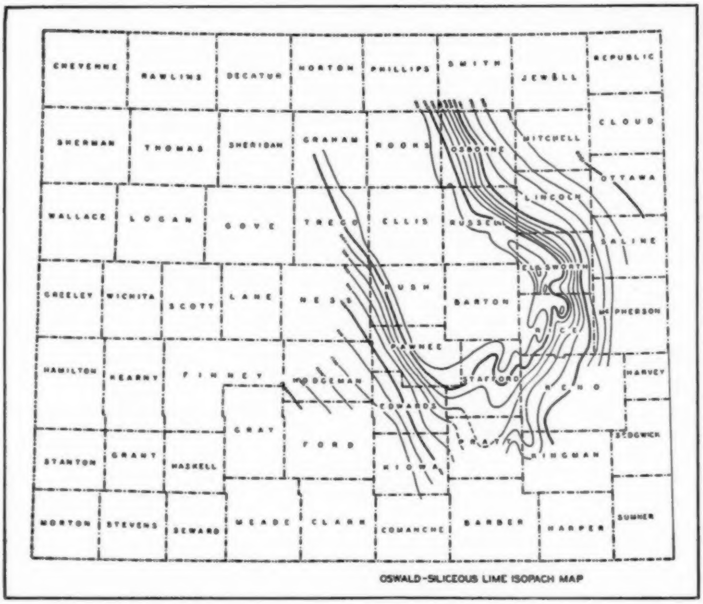

FIG. 4.—Isopach map showing interval between top of Oswald limestone and top of "Siliceous lime." Contour interval, 100 feet. (March, 1935.)

with the broad warping of the uplift during other periods of its structural growth.

Figure 4, showing by contours the interval between the top of the Oswald limestone and the top of the "Siliceous lime," or younger units, where the latter is absent, depicts the structural growth of the uplift at the beginning of Virgil sedimentation. It also represents the structure of the top of the "Siliceous lime" in early Virgil time.

In Figure 4 the area within the 400-foot contour has been left blank. Within this area there are many places where the interval is less

than 300 feet and several in which it is about 250 feet. These of course are on the most pronounced local structures. Comparison of Figures 2, 3, and 4 shows that the nuclear area lies almost altogether within the 400-foot contour. Moreover nearly all the oil production on the uplift, irrespective of producing horizon, has been found within the 400-foot contour.

Figure 5 shows the present structure of the top of the Fort Riley

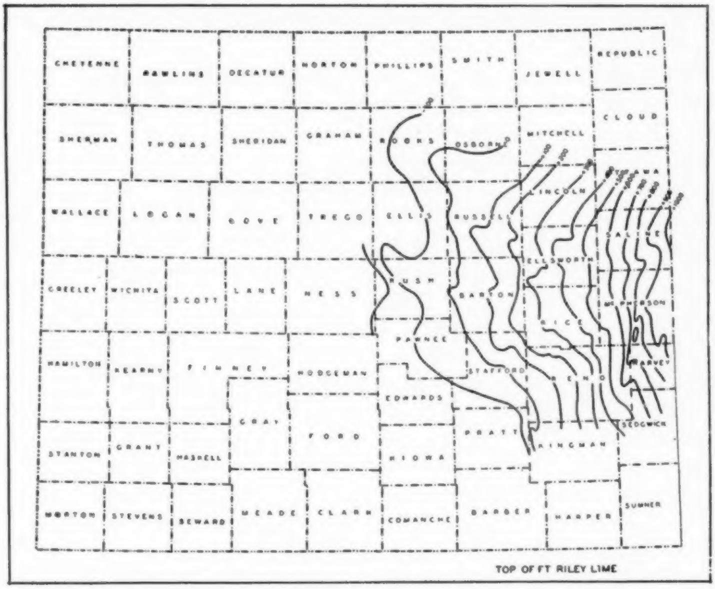

FIG. 5.—Structural contour map of top of Fort Riley limestone. Contour interval, 100 feet. (March, 1935.)

limestone. The nuclear area can be seen as a northwestward trending nose through Rice, Ellsworth, Barton, Russell, Osborne, Rush, Ellis, and Rooks counties. It is noteworthy that the Rush and Russell ribs can be distinguished in an indefinite manner at this horizon. The McPherson anticline stands out prominently. The bulge in the contours in western Kingman County is at the Cunningham oil field. Unfortunately control is meager in the deeper portion of the Salina basin, but this map brings out the fact that it is primarily a depositional feature of pre-Mississippian age.

Contouring of other stratigraphic markers in the Permian above

the Fort Riley limestone gives relationships similar to Figure 5, but suggests less and less warping in later time. There is some evidence, which in some respects is confusing and contradictory, that the area of the Central Kansas uplift has been broadly elevated since Cretaceous time. This may be seen by a study of the Cretaceous structure of Russell County.[29] Cretaceous rocks in the southern portion of the county, overlying the nuclear area of the uplift, dip at the rate of 5 feet per mile toward the north-northeast, whereas in the northern part of the county, overlying the northeast flank of the uplift, the dip is about 12 feet per mile.

The term warping, as used in this paper, implies some subsidence of basinward areas as well as elevation of the nuclear area. Just as this warping has taken place periodically since pre-Cambrian time, so has true folding in general northeast and southwest directions occurred several times since the first folding and faulting of post-Morrow pre-Atoka time. Up to date all of the important production of oil and gas has been found only on those parts of the northeast-southwest folds which lie within or very close to the nuclear part of the uplift.

GEOLOGIC HISTORY

An attempt to outline the geologic history of the Central Kansas uplift at present may appear premature, as information on this structural feature, which has been assembled as the fruit of a decade of drilling, is incomplete and ever growing. However, the writer believes that enough has been learned to present a reasonably accurate chronology of the geologic processes which have been at work in the area. Where the local record is missing recourse must be had to surrounding regions.

Studies at the north in the Upper Mississippi Valley region and at the south in the Arbuckle Mountains of Oklahoma show that these areas in early Paleozoic time had similar geologic histories. No great unconformity in the sequence of limestones, dolomites, and sandstones that represent Cambrian and Ordovician deposition is evident up to the top of the Prairie du Chien group of the Upper Mississippi Valley or the top of the Arbuckle group of the Oklahoma section. This widespread post-Canadian erosional interval is represented in Kansas by the unconformity at the top of the "Siliceous lime."

In the Ozark region of Missouri several unconformities occur between the top of the pre-Cambrian and the top of the Canadian. These indicate periods of emergence during which many or all beds above the crystalline rocks were stripped off. Overlap relations developed as

[29] W. W. Rubey and N. W. Bass, *op. cit.*

the result of later submergence. Such conditions have been found in eastern Kansas on the Chautauqua arch between the Ozarks and the Central Kansas uplift. Thinning of the basal sand toward the higher portions of the uplift is established and in at least one well the "Siliceous lime" overlaps the basal sand and rests directly on pre-Cambrian quartzite. The correlation of the "Siliceous lime" in wells on the uplift with the Cotter and Jefferson City formations of the Missouri section has been made by several workers and indicates the absence of the older Ozarkian and Cambrian formations in part. The uplift was evidently a land mass throughout a large part of early Paleozoic time, while the thicker dolomites, limestones, and sandstone of the Arbuckle group were forming in southern Oklahoma. Apparently the Central Kansas uplift is more closely related in geologic history to the Ozarks than to the areas at the north or south.

The work of Morgan has shown that the pre-Cambrian rocks of Kansas consist of granite, arkose, schist, quartzite, and red clastics, and that in general the lighter granite and quartzite occupy the nucleus of the uplift. In general the schist and thicker arkoses and red clastics have been found on the flanks or saddles of the warped area.

It is consistent with these facts to consider the forerunner of the uplift as a series of more or less parallel batholiths which in pre-Cambrian time were intruded into the younger schist and quartzite. Truncation has laid bare the granite core and produced the arkose and red clastics which have accumulated in depressions, to a thickness of a few hundred feet, while simultaneously 2,000 feet of red clastics were laid down in the Upper Mississippi Valley. The number of periods of uplift and erosion in pre-Upper Cambrian time is unknown.

The first deposit of the Paleozoic sea was a loosely cemented, well rounded, basal sandstone, which is of variable age in different parts of the Mid-Continent region, but which is probably of Middle Ordovician age on and close to the uplift. It appears to have the characteristics of a transgressive overlap. It covered all or nearly all the granite knobs, but was laid down in greater thickness on the flanks of the uplift. Concentration of lime in the sea caused precipitation of a transitional sandy dolomite. Dolomite-forming conditions persisted throughout most of the remainder of Canadian time, although occasional oscillations of the sea resulted in the formation of arenaceous beds. Locally the dolomite overlapped the basal sand to rest directly on pre-Cambrian rocks.

After the close of Canadian time there was a general emergence of the Central Kansas uplift. This period of erosion is also represented in the Ozark, Arbuckle, and Upper Mississippi Valley regions. It is quite

probable that all of the "basal sand" and "Siliceous lime" were stripped off parts of the nuclear area; certainly there was more truncation here than in parts of southern Kansas and northern Oklahoma where thicker sections are known. The effect was a warping of the whole uplift area in approximately northwest and southeast directions.

The seas which deposited the Simpson beds in northern Oklahoma and southern Kansas did not cover the uplift until late in Simpson time. Sand and green shale were the deposits of these seas. A minor hiatus occurred, to be followed by the deposition of those beds which are here grouped under the term "Viola lime." Minor breaks are evident within the "Viola lime," and one is seen at the top of the Maquoketa shale. Deposition of Siluro-Devonian (Hunton) strata probably covered a broad area in the Mississippi Valley, but post-Hunton pre-Kinderhook erosion has removed these rocks over much of Kansas and northern Oklahoma, including all of the Central Kansas uplift. Uplift also occurred in the Ozarks, and in the Seminole and Arbuckle areas of Oklahoma, at the end of Siluro-Devonian time.

There are no important breaks in evidence within the Mississippian in Kansas. However, the post-Wapanucka pre-Atoka break (Wichita disturbance) is represented here. At that time the Central Kansas uplift was broadly elevated and folded along northeast-southwest trends. Simultaneously the Nemaha Granite ridge was folded and faulted, and similar movements took place along the McPherson and Ellsworth anticlines, which are approximately uniformly spaced between the uplift and the Nemaha ridge. Evidently these folds overlie zones of weakness in the basement rocks and this early Pennsylvanian folding was merely a resurrection of earlier folds. Broad warping of the uplift and folding of its cross-grained northeast-southwest anticlines continued throughout Pennsylvanian and Permian time. The most prominent of these periods of structural growth seems to have occurred in post-Missouri time and is represented by the post-Oswald unconformable zone in central Kansas.

Post-Permian westward tilting has had little effect on the uplift except that it has left thinner red beds on the east side of the uplift than on the west side and consequently caused the lower horizons to be at greater depth on the west and southwest. Post-Cretaceous movements have revived the northeast-southwest anticlines and have flattened the regional dip of Cretaceous beds over the nucleus of the uplift. This has been effected most likely largely by settling. The last period of structural growth of the Central Kansas uplift is not definitely known, but it has been a living, growing feature since pre-Cambrian time.

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TYPES OF FOOTHILLS STRUCTURES OF ALBERTA, CANADA[1]

THEODORE A. LINK[2]
Calgary, Alberta

ABSTRACT[3]

Several types of Foothills structures and their relationship to Rocky Mountain structure are illustrated by cross sections, maps, and selected photographs. The types selected are, for the most part, located south of Bow River, and are such structures as have been tested by deep drilling and mapped in detail. The preponderance of overthrust sheets underlain by low-angle sole faults, some of which may be warped or folded, is established. Major underthrust faults, overturned anticlines, underfolded uplifts with major overthrust faults are described.

Brief mention is made of minor structures such as high-angle and discoidal faults, sharp and broad-crested anticlines, and other types. Metamorphism, carbon ratios, salients and recesses, and other topics are also discussed.

INTRODUCTION

Royalite No. 4, the "wonder well" of Turner Valley, Alberta, blew into production from a porous zone in the Paleozoic limestone during October, 1924. Before that date all geological investigations in the Alberta Foothills belt were conducted under the premises that production of petroleum or gas should be expected in the "Dakota" (Blairmore), or in sands associated with the Kootenay coal beds. The unexpected production from the Paleozoic limestone immediately altered the whole situation and gave petroleum geological prospecting a different aspect in this part of Alberta. It also gave rise to a period of more intensive and renewed field investigation and drilling for oil. Outside of Turner Valley approximately 45 test wells had been drilled in the Foothills prior to 1924, but many of these were abandoned at shallow depths. Since that time approximately 50 new locations have been made, but to date Turner Valley is the only producing Foothills oil field. A considerable number of these later tests were also abandoned at shallow depths, and many were poorly located geologically, although the majority were more reasonable tests than the former.

[1] Published by permission of O. B. Hopkins, chief geologist, Imperial Oil, Limited, Toronto, Ontario.

[2] Geologist in charge, western Canada.

[3] Presented before the Association at the Wichita meeting, March 22, 1935. Manuscript received, July 16, 1935.

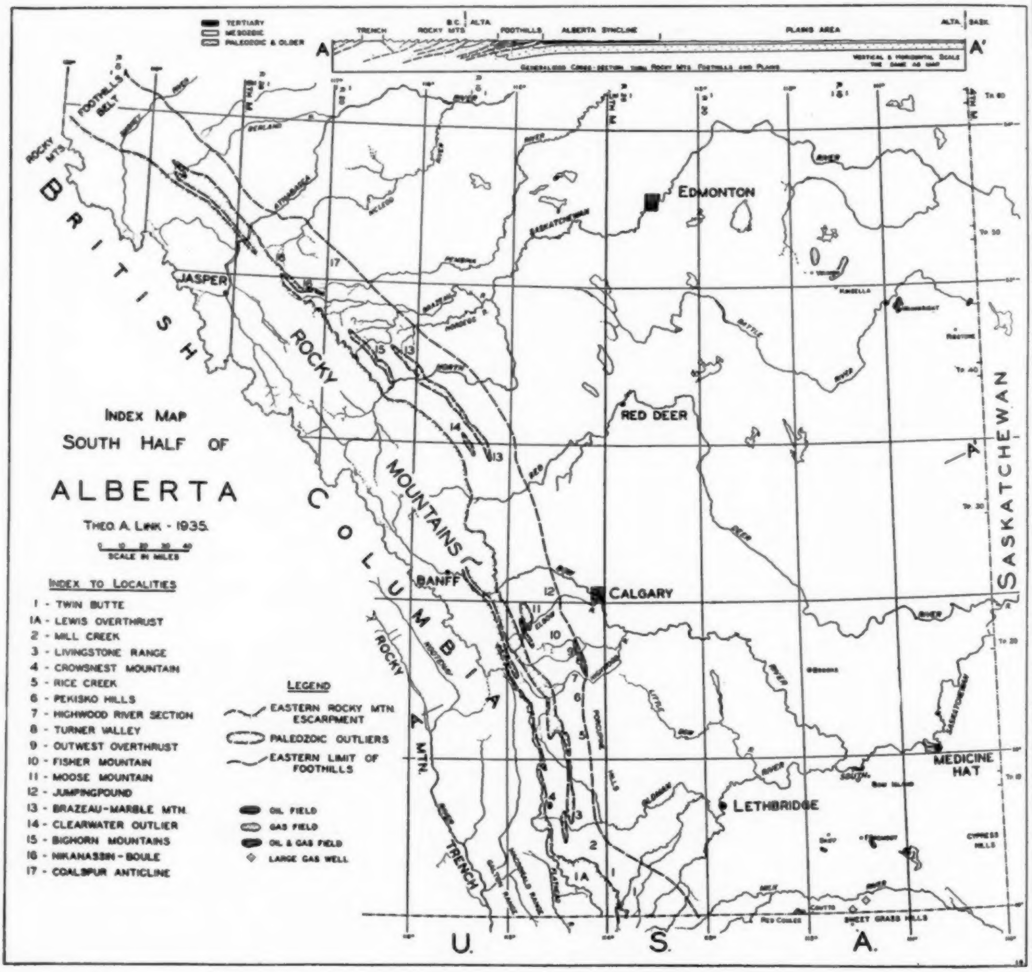

FIG. 1.—Index map of south half of Alberta, showing relationship between Rocky Mountains, Foothills, and Plains. Numbers indicate position of structures and features discussed in this contribution. Oil and gas fields in Plains area also indicated. Position of generalized cross section at top shown by letters *AA′*.

The object of this contribution is to survey as briefly as possible what has been done in the light of recently accumulated geological data, and to compare, by means of cross sections and maps, several types of Foothills structures. When one considers that knowledge of the Turner Valley field is based on accurate well logs from more than 125 locations, detailed surface geology, diamond-drill structure core-holes, three different attempts with geophysical prospecting, aerial photographs, some directional and many acid-bottle bore-hole surveys and yet, in spite of all these data, there are still many debatable questions, it seems futile to attempt interpretation of other Foothills structures where the surface geological data have been augmented, in some cases, by only one deep test. However, the knowledge and experience gained from Turner Valley have been of considerable aid in the interpretations of the structures described in this contribution.

The structures described and figured range from the most southerly portion of the Alberta Foothills as far north as Township 49, a distance of approximately 300 miles, although the majority are located south of Bow River, where recent drilling activities were concentrated. The cross sections and maps submitted are all based upon very exhaustive and detailed field mapping, and at least one deep test hole for each section. The photographic illustrations have been selected from several hundred negatives taken by the writer.

Acknowledgments for the data used on the various structures are given individually. The writer has examined all of them personally and mapped the majority of them. A great number of the well-log records were compiled by P. D. Moore, formerly resident geologist for the Royalite Oil Company, Limited, at Turner Valley.

In his recent publication "Oil and Gas in Western Canada" (2nd edition), G. S. Hume[4] describes most of the structures covered in this contribution but, as pointed out in a review by the writer, the omission of cross sections and illustrations makes it difficult for those not familiar with the area to arrive at a more concrete conception of typical Foothills structures. With this in view the following selected types are submitted with illustrations, cross-sections, and a few selected photographs.

Stratigraphic column.—No details of stratigraphy will be given in this contribution, but abridged geologic sections are submitted on several of the cross sections and maps for ready reference. In general there is a gradual thickening of beds toward the mountains and northward.

[4] G. S. Hume, "Oil and Gas in Western Canada," *Geol. Survey of Canada, Economic Geology Ser. 5, Pub. 2128.*

TWIN BUTTE OVERTHRUST SHEET

The Twin Butte overthrust sheet is the most southerly structure of the Canadian Foothills belt to receive serious consideration and exploration. It is situated in Ts. 1–6, Rs. 28–30, West of the 4th Meridian, and Rs. 1 and 2, West of the 5th Meridian (locality 1 on Index Map, Fig. 1). It appears to be a very wide, flat-topped, Colorado shale anticline, flanked on the west by a Belly River rim rock and faulted against irregular *west-dipping* Belly River ridges on the east. The structure swings sharply to the west in T. 5, R. 30, West of the 4th Meridian, where Kootenay beds are observed faulted over Colorado shale. At the Christie coal mine, near Pincher Creek, one may observe the sole-fault plane underlying this structure dipping 18°–34° SW. The fault plane, overlain by the coal, is so highly polished and smoothly slickensided that it is almost impossible to walk up the surface without support. The coal seam, which acted as a lubricant, dips *southwestward* at an angle of 25°–35°.

Five deep tests were drilled on this thrust sheet which, from surface data, has all appearance of being a promising structure. The locations are: Twin Butte No. 1, Twin Butte No. 2, Waterton Lakes No. 1, Drywood No. 1, and Yarrow No. 1. At Twin Butte No. 2 and Waterton Lakes No. 1, drilling commenced and was stopped in the Colorado shale at depths of 4,375 and 4,605 feet without encountering older formations. High-angle thrust faults within the Colorado shale were regarded as the explanation of this condition as late as 1929.

At Twin Butte No. 1, drilling began in the Colorado shale, and stopped in that formation after passing from Kootenay beds (coal series) through the sole fault at a depth of 2,680 feet (Fig. 2, A). Unfortunately, the log of this drill hole had not been interpreted correctly before the drilling of Drywood No. 1, which is located less than ¼ mile from it. At Drywood No. 1 the sole fault was also encountered at 2,680 feet, where the drill passed from Kootenay beds (at the coal series) into Colorado shale. The hole was abandoned at a depth of 3,030 feet in Colorado shale. An abridged geologic column for this area is shown in Figure 2, C.

Yarrow No. 1 was located after drilling 14 diamond structure core holes on this overthrust sheet as shown in Figure 2, A. The sole fault was encountered at a depth of 3,870 feet, the drill passing here from lower Blairmore back into Colorado shale. It is highly probable that at Twin Butte No. 1 and Waterton Lakes No. 1 the same low-angle thrust fault was encountered without being recognized because of Colorado shale thrust over on itself.

The cross section, Figure 2, A, and the geologic column, Figure

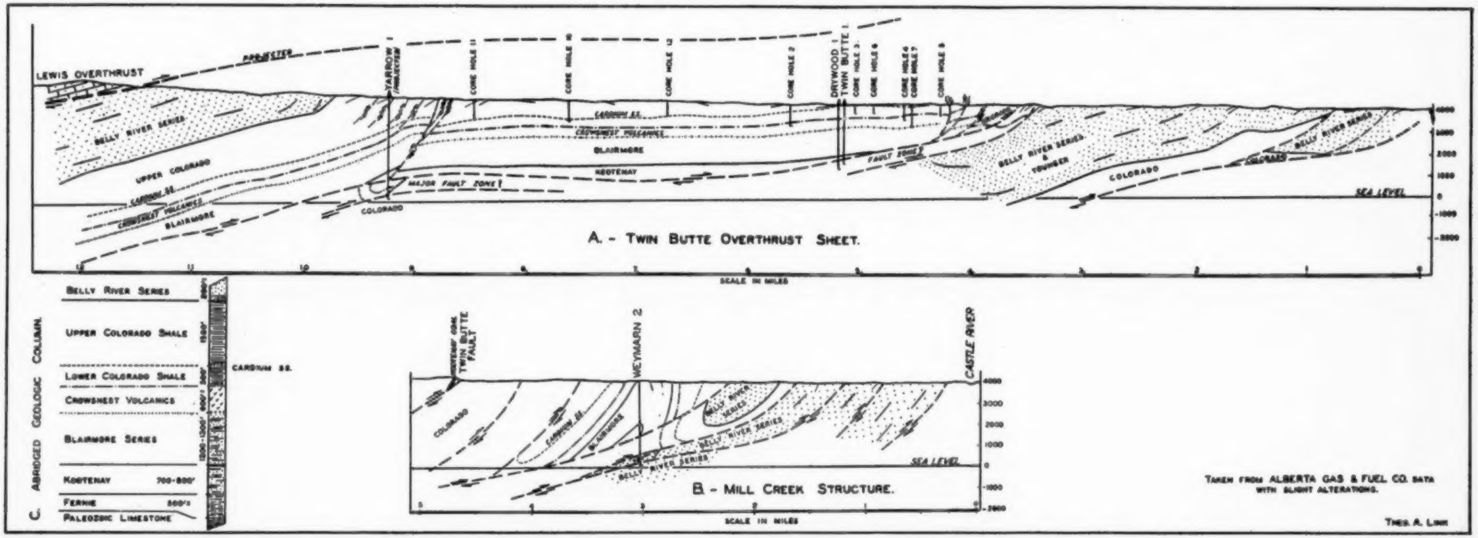

FIG. 2.—*A*. Cross section of Twin Butte overthrust sheet. Lewis overthrust fault is projected eastward beyond its surface trace. Note that Twin Butte fault follows Kootenay coal bed, which acted as lubricant. *B*. Cross section of Mill Creek overthrust and overturned anticline. Surface trace of Twin Butte fault shown on left. *C*. Abridged geologic column for southern Foothills area.

2, C, are based on detailed surface geological mapping by Linn Farish, L. Kemnitzer, H. M. Kirk, and H. F. Moses, geologists of the Alberta Gas and Fuel Company, extensive diamond structure core drilling carried on under their supervision, and the deep test holes referred to.

The Twin Butte structure is of particular interest for several reasons. In the first place it lies in the shadow of the Rocky Mountain front, which is here delineated by the escarpment caused by the great Lewis overthrust (Figs. 1 and 2). It is a thrust sheet of considerable magnitude with essentially flat-lying beds, very similar to the Lewis thrust sheet itself. However, it is composed of a wholly different type of rock. The Lewis thrust sheet has at its base competent, hard and rigid pre-Cambrian rocks capable of primary or large-scale stress transmission. The major portion of the Twin Butte overthrust sheet is composed of the incompetent Colorado shale, which is overlain by the more competent Belly River series. The minimum displacement of the Twin Butte overthrust sheet is 4 miles. It is difficult to understand how this sheet could have travelled so far *intact* without having crumpled up into folds, and being cut by adjustment faults, as is the case in most parts of the Foothills, in particular east of the surface trace of the Twin Butte sole fault.

J. S. Stewart,[5] who regarded this structure as a broad, flat-topped anticline bordered on the east by a high-angle thrust fault, suggested that its competency was imparted by the formerly overlying Lewis overthrust sheet. This explanation is, in the writer's opinion, a wholly adequate and reasonable one, and it fits the facts with the recently acquired knowledge regarding the low-angle Twin Butte sole fault. It appears that the competent Lewis overthrust sheet extended eastward at least as far as the present surface trace of the Twin Butte thrust fault. From that point on eastward to the edge of the Foothills the rocks are much more closely faulted and folded, suggesting either numerous high-angle slice faults extending downward to one underlying master sole fault, or numerous thrust sheets emerging closely spaced (Fig. 2, A).

It appears highly probable that the part of the Twin Butte thrust sheet which is observable today had a minimum thickness of about 6,500 feet, or 1.25 miles. This inference is drawn on the assumption that the dip of the Lewis overthrust fault may be extended eastward at about the same rate as is observed in the mountains. The thickness of the Lewis overthrust sheet where it overlay the Twin Butte sheet is not known. When stresses were relieved by movement along the sub-

[5] J. S. Stewart, "Geology of the Disturbed Belt of Southwestern Alberta," *Geol. Survey of Canada Mem. 112, Pub. 1740* (1919), p. 51.

sequently developed Twin Butte (coal-lubricated) sheet, the overlying Lewis overthrust sheet rode along and imparted the necessary rigidity or competency. The relationship between the Lewis and Twin Butte thrust sheets is further discussed in a later part of this contribution.

MILL CREEK STRUCTURE

North and east of the Twin Butte overthrust sheet in T. 6, Rs. 1 and 2, West of the 5th Meridian, is a small anticlinal uplift exposing a core of Blairmore beds (Fig. 1, locality 2). On this structure was located the old Mount Royal well No. 1, which was abandoned at a shallow depth in favor of a new location called Weymarn No. 2. This narrow and short uplift is an excellent example of an overturned anticlinial fold underlain by a major sole fault. Drilling at Weymarn No. 2 commenced in the Blairmore series and, due to high dips, overturned beds, and minor faulting, 2,000 feet of section were drilled before the Kootenay coal was first encountered. Overturning of the beds above the sole fault apparently caused a duplication of the coal at 2,540 feet, and at 2,580 feet a fault was encountered. Between 2,580 and 3,500 feet Blairmore or Kootenay beds were again drilled, and at 3,500 feet a major fault of considerable throw was encountered beneath which lay Belly River beds. A total depth of 3,870 feet had been drilled when the hole was abandoned in the Belly River series.

The cross section submitted herewith (Fig. 1, B) illustrates, as nearly as possible, the nature of this overturned anticline and the faulting. It is based on data obtained from the Alberta Gas and Fuel Company geologists, and the well log prepared by J. G. Spratt. The structure is submitted primarily to illustrate a decidedly narrow, overturned, anticlinal fold which is a common type, but not generally favored by geologists.

RICE CREEK STRUCTURE

The Rice Creek structure, located in T. 14, R. 2, West of the 5th Meridian, is one of the most clearly defined surface anticlines to be found in the Foothills area of Alberta (locality 5, Fig. 1). It is an *apparent* example of an Appalachian or Wyoming type of open fold exposing a Colorado shale basin almost completely surrounded by a high, prominent, and well defined Belly River rim rock. The vertical aerial view (Fig. 3) shows clearly the nature of the fold as seen from above. There is no suggestion or definite evidence of major faulting to be observed in the immediate vicinity of this small structure. However, in the light of recently accumulated data, one *might* suspect an underlying sole fault to be encountered at a considerable depth. The results

FIG. 3.—Vertical aeroplane photograph of Rice Creek structure. Note how Belly River sandstone rim rock closes toward south. Irregular white spot in center of amphitheater is drilling mud from Rice Creek No. 1 location. (Photo by Western Canada Airways.)

obtained in the well chosen Rice Creek No. 1 location are startling, but nevertheless the evidence from the well samples is undeniable and positive. It seems incredible that a major sole fault would be encountered at that location at the relatively shallow depth of 710 feet, where the drill passed from Colorado shale into beds of the Upper Belly River series, as shown in Figure 4. However, with the knowledge of results obtained at Twin Butte and other structures described in this contribution, one assumes the attitude that low-angle thrust faults may be encountered where least expected.

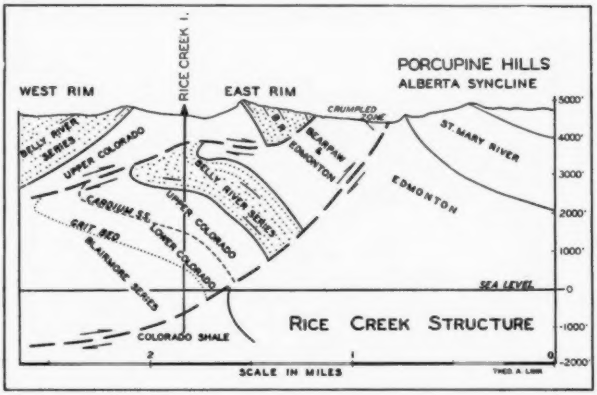

FIG. 4.—Cross section of Rice Creek structure showing two low-angle thrust faults which were encountered at depths of 710 and 5,230 feet.

As shown on the cross section (Fig. 4), the drill, after passing through the relatively shallow thrust sheet, encountered a normal Belly River section from 710 to 1,940 feet, and at that depth the top of the Colorado shale was reached. This contact is transitional and might be placed 40 feet above or below the figure given. At 3,240 the Cardium sandstone was encountered, and at 4,040 the Grit bed, which is the top of the Blairmore series, was reached. The thickness indicates that the Colorado shale was drilled on a relatively low dip, since it measured only 2,100 feet, or about 400 feet less than at Turner Valley. This figure is comparable to the thickness obtained at Twin Butte (Fig. 2, C). From 4,040 to 5,230 feet Blairmore beds were encountered in a normal sequence with carbonaceous or coaly material near the 5,230-foot mark. At 5,230 feet another major thrust fault was met when the drill passed back into Upper Colorado shale in which drilling was halted at a total depth of 5,740 feet. If it had not been for this last

thrust fault the Paleozoic limestone might have been reached close to the 6,000-foot level, but under present circumstances it lies at least 8,000 feet deep—probably 10,000 feet or more.

The only place assignable to the surface trace of these two major fault planes lies in the highly crumpled and disturbed zone occupied by a small creek valley about a mile farther east. It appears highly probable that this is the same zone of major faulting which extends northward for 30 miles to the Highwood River, where the Bearpaw

FIG. 5.—View of Highwood River gorge showing excellent and continuous outcrops of Colorado and Blairmore beds.

shale is highly folded and faulted, with inliers of Edmonton beds and up folds of the Belly River series. If this is the fact, it is highly probable that the main part of the Highwood uplift, to be described later, is also underlain by a major fault plane or zone. The Rice Creek structure appears to be the most southerly part of that thrust sheet. The cross section (Fig. 4) was prepared from the aerial photograph, a detailed map by J. S. Stewart for the Imperial Oil, Limited, and the well log interpreted by the writer.

HIGHWOOD-WAITE VALLEY UPLIFT

What is probably one of the largest individual overthrust sheets in the Foothills area is the so-called "Highwood-Waite Valley uplift." The surface expression of this structural unit appears to be at least 9

miles wide and 42 miles long. There is the possibility that it may in reality consist of several thrust sheets overlapping one another in such a manner as to avoid recognition as separate units. On this thrust sheet several wells have been drilled deep into the Paleozoic limestone without encountering the underlying projected or hypothetical thrust fault. The limestone lies closer to the surface on this uplift than in Turner Valley, but to date the Paleozoic limestones and dolomites have yielded only small volumes of gas and few showings of oil with considerable sulphur water from this uplift.

The section along Highwood River in T. 18, Rs. 2 to 4, West of the 5th Meridian, which lies west of the south end of Turner Valley, exposes across the Highwood-Waite Valley uplift one of the most complete successions of outcrops to be observed in the Foothills belt (locality 7, Fig. 1). It is a section replete with problems of structural geology and might be termed "a geologist's paradise," were it not for the fact that it defies detailed interpretation at depth. With such complete surface data available, augmented by three deep drill holes along the same line of section, it is still impossible to determine definitely the existence or non-existence of an underlying master sole fault. Because of this, the sole fault shown in Figure 6 is drawn with reservations, as indicated by the question marks. On the section is shown the previously mentioned zone of intense folding and faulting lying east of the Highwood uplift and separating it from the extreme south end of the Turner Valley structure. This crumpled zone consists mostly of Bearpaw shale and is in line with the surface trace of the Outwest sole fault which overlaps the west rim of the Turner Valley sheet (Fig. 7). In view of this relationship, it is highly probable that the same sole fault underlies the Highwood uplift. As already mentioned, it extends south as far as Township 14, and its projection underneath the Rice Creek structure is established by the results obtained at the deep test drilled on that structure. It appears that the Rice Creek structure, which is closed on the south end, is the most southerly part of the Highwood uplift, and that the plane of the sole fault rises gradually in that direction, where it was reached at the shallow depth of 710 feet. At the Imperial-Highwood No. 1 location (Fig. 6) the top of the Paleozoic limestone was encountered at a depth of 4,223 feet, and at 4,440 feet the diamond drill passed back into Fernie shale inverted. Drilling was not carried deep enough to establish the presence of a sole fault, but the data are interpreted as indicating the "drag" on the upthrown side of a major fault.

The cross section shown in Figure 6 is based on a detailed survey (12 inches to the mile) of the Highwood River section by the writer, and well-log examinations by P. D. Moore.

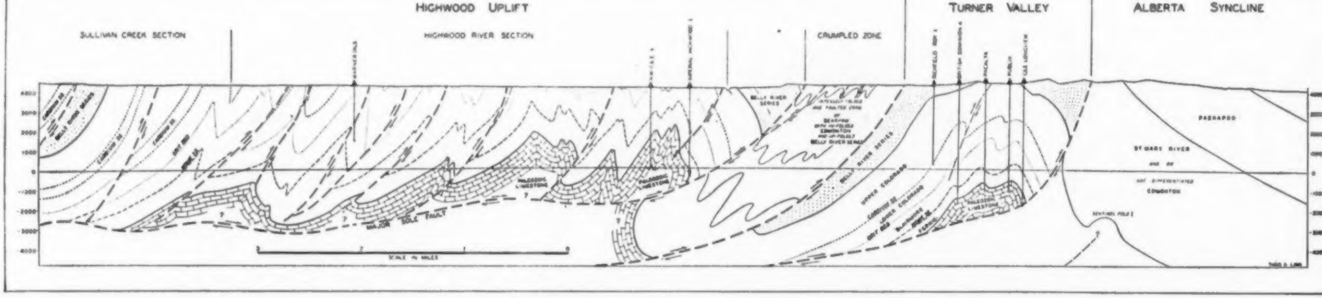

FIG. 6.—Cross section through Highwood-Waite Valley structure as mapped along Highwood River, and south end of Turner Valley structure. Low-angle fault below Highwood uplift is hypothetical.

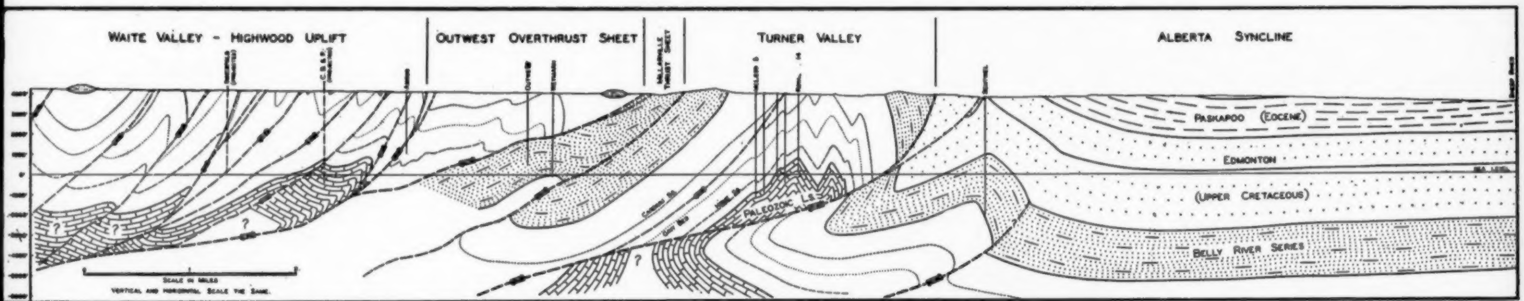

FIG. 7.—Cross section through central Turner Valley, Outwest overthrust sheet, and Highwood-Waite Valley uplift, as mapped along south fork of Sheep River. Compare this with Figure 6. Note how Outwest overthrust sheet pinches out toward south and merges into crumpled zone east of Highwood uplift.

FIG. 8.—Highly crumpled anticline in Jumping Pound sandstone of Lower Colorado shale on Highwood River.

PEKISKO HILLS STRUCTURE

When erosion shall have removed another 1,200 feet from the Foothills there will appear an outlier of Paleozoic limestone as an outer Foothills fold where Pekisko Hills No. 1 is now being drilled (Fig. 1, locality 6). The Pekisko Hills structure appears to be the highest part structurally of the large Highwood uplift (Fig. 9). Lower

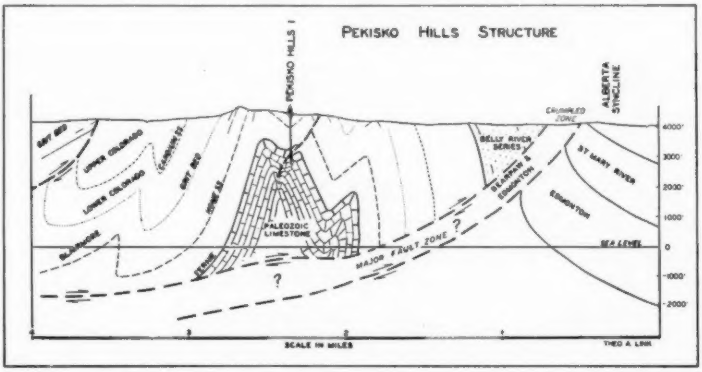

FIG. 9.—Cross section of Pekisko Hills structure which is structurally one of highest parts of Highwood uplift. Note steeper dips on west flank of structure. Underlying sole fault is hypothetical, but appears to be same as shown on Rice Creek structure.

Blairmore sandstone ledges (Home sandstone, etc.) cropping out near the top and the flanks of this topographic "high," indicate a tightly folded and slightly faulted anticlinorium which has a west flank steeper than the east.

In spite of the relatively shallow depth at which the Paleozoic limestone was reached at this location only 4 million cubic feet of dry gas have been encountered. The hole has been carried to a depth of 2,345 feet, or 1,275 feet into the Paleozoic, and it is planned to deepen it. Other wells drilled on the Highwood uplift obtained some gas and much sulphur water, but to date Pekisko Hills No. 1 has not encountered water.

As previously stated, the presence of a sole fault underlying the Highwood uplift has not been established, but a belt of highly folded and faulted Bearpaw shale is to be observed east of the Highwood uplift from Township 18 south to Township 14. At Rice Creek, already referred to, this zone is regarded as the surface manifestation of a sole fault. The writer believes, on the basis of similar conditions in Turner Valley, that this uplift is also a major thrust sheet of considerable size and thickness, as shown in Figures 6, 7, and 9. This interpretation may be questioned by other geologists, but to date there is no definite proof either for or against it, excepting the previous observations at Rice Creek and Imperial-Highwood No. 1 which, to the writer, favor the sole-fault theory. The cross section shown in Figure 9 is based on a detailed map prepared by J. S. Stewart, and the well log prepared by the writer.

TURNER VALLEY STRUCTURE

On the Turner Valley overthrust sheet previously described,[6] additional drilling has verified, within reasonable limits, the interpretations submitted (Fig. 1, locality 8). The relationship between this structure, the Outwest thrust sheet, and the northern part of the High wood-Waite Valley uplift, is shown in Figures 6 and 7. At the extreme south end of the Turner Valley field, additional drilling has added enough data to construct an accurate cross section. The probable relationship between it and the Highwood uplift as exposed along the Highwood River is shown in Figure 6. The contention of a probable absence of direct communication between the Paleozoic limestone of the Turner Valley thrust sheet and the Highwood uplift received additional weight after the drilling of the Pekisko Hills well into the limestone on the Highwood uplift without encountering wet-

[6] Theodore A. Link and P. D. Moore, "Structure of Turner Valley Gas and Oil Field, Alberta," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 18, No. 11 (November, 1934), pp. 1417–53.

gas production comparable to that obtained in Turner Valley. The combination of structural conditions and the oil and gas accumulations obtained in Turner Valley still appear to be a unique condition not found to be duplicated elsewhere in the Foothills area.

FIG. 10.—West Belly River rim rock of Turner Valley along Sheep River.

A surface geologic map and stratigraphic column of Turner Valley is submitted (Fig. 14) for comparison with the Jumping Pound structure to be described later.

The Turner Valley structure is a highly faulted, closely folded, anticlinal fold, bounded on the east by a major overthrust sole fault which underlies the entire structure or a greater part of it. On the west this structure is bounded by one or two similar overthrust sheets. The north end of Turner Valley is merely an *apparent* or physiographic continuation of Turner Valley proper. It is one of the westerly overthrust sheets cutting obliquely across the northward plunge of the main structure.[7]

OUTWEST OVERTHRUST SHEET

In the previous contribution[8] referred to, mention was made of the Outwest overthrust sheet which overlaps the western edge of the Turner Valley thrust sheet (Fig. 1, locality 9). Two holes were drilled on this structure along Sheep River, directly west of the central part

[7] Theodore A. Link and P. D. Moore, *op. cit.*, p. 1423.

[8] Theodore A. Link and P. D. Moore, *op. cit.*, p. 1421 and Fig. 2.

of Turner Valley, where the section exposes a decidedly asymmetrical anticline within the Colorado shale. The west flank has a dip of 10°–20°, while the east flank dips as much as 55°. At the New Black Diamond Weymarn No. 1 location, drilling commenced on the east limb in Lower Colorado shale, and at a depth of 2,160 feet the drill passed from that formation through the sole fault into Belly River beds (Fig. 7). At the Outwest No. 1 location, drilling commenced on the west flank of the surface structure in Upper Colorado shale. At 450 feet the Cardium sandstone was encountered, at

FIG. 11.—Typical winter view of Foothills. High, conspicuous ridge of Belly River series on west flank of Waite Valley uplift.

1,910 feet the top of the Blairmore was reached, and at a depth of 2,450 feet the drill passed through the sole fault into Belly River beds. The fault underlying this thrust sheet appears to extend southward into the crumpled zone which may be the same one as that underlying the Highwood uplift previously described. The Belly River coal series crops out at the surface trace of this fault and was also encountered at both of the locations previously mentioned on the downthrown side of the fault zone, thus affording another example of coal beds acting locally as lubricants along a bedding-plane fault.

FISHER MOUNTAIN THRUST SHEET

One of the most interesting structures of the inner Foothills belt to be tested by the drill is the Fisher Mountain uplift in T. 21, R. 2,

West of the 5th Meridian (Fig. 1, locality 10). At this locality a prominent topographic "high" in the form of a steep ridge exposes lower

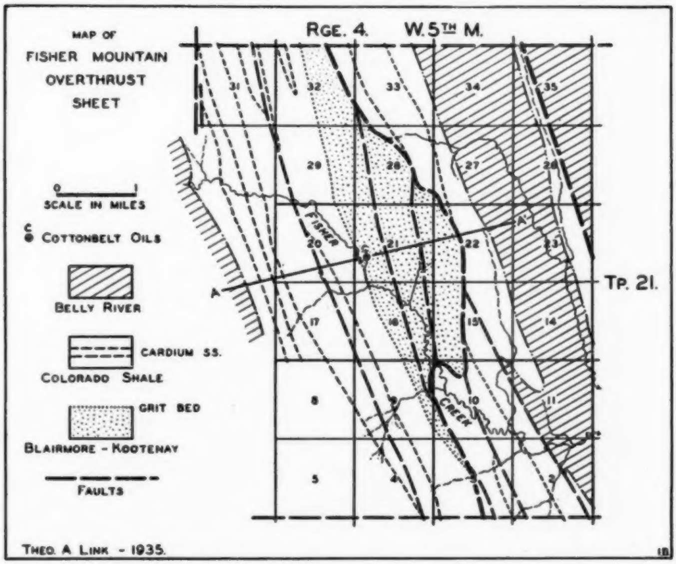

FIG. 12.—Geologic map of Fisher Mountain overthrust sheet. Note sinuous course of trace of major sole fault. Cross section AA′ shown in Figure 13.

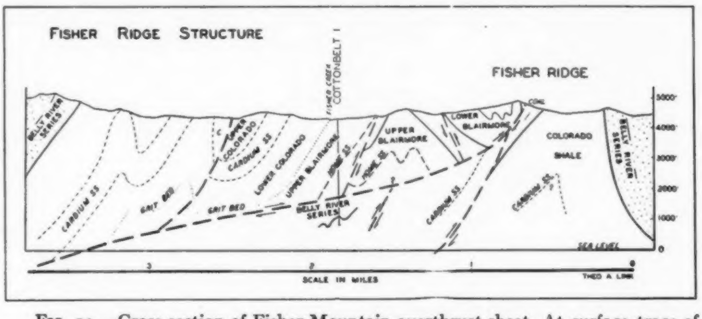

FIG. 13.—Cross section of Fisher Mountain overthrust sheet. At surface trace of fault, Kootenay beds are faulted against Colorado shale, and in Cottonbelt well, Kootenay is thrust over Belly River beds.

Blairmore and Kootenay beds faulted against Colorado shale. The surface trace of this fault lies approximately 7 miles west of the eastern edge of the Foothills belt. As shown in Figure 12, the surface trace of

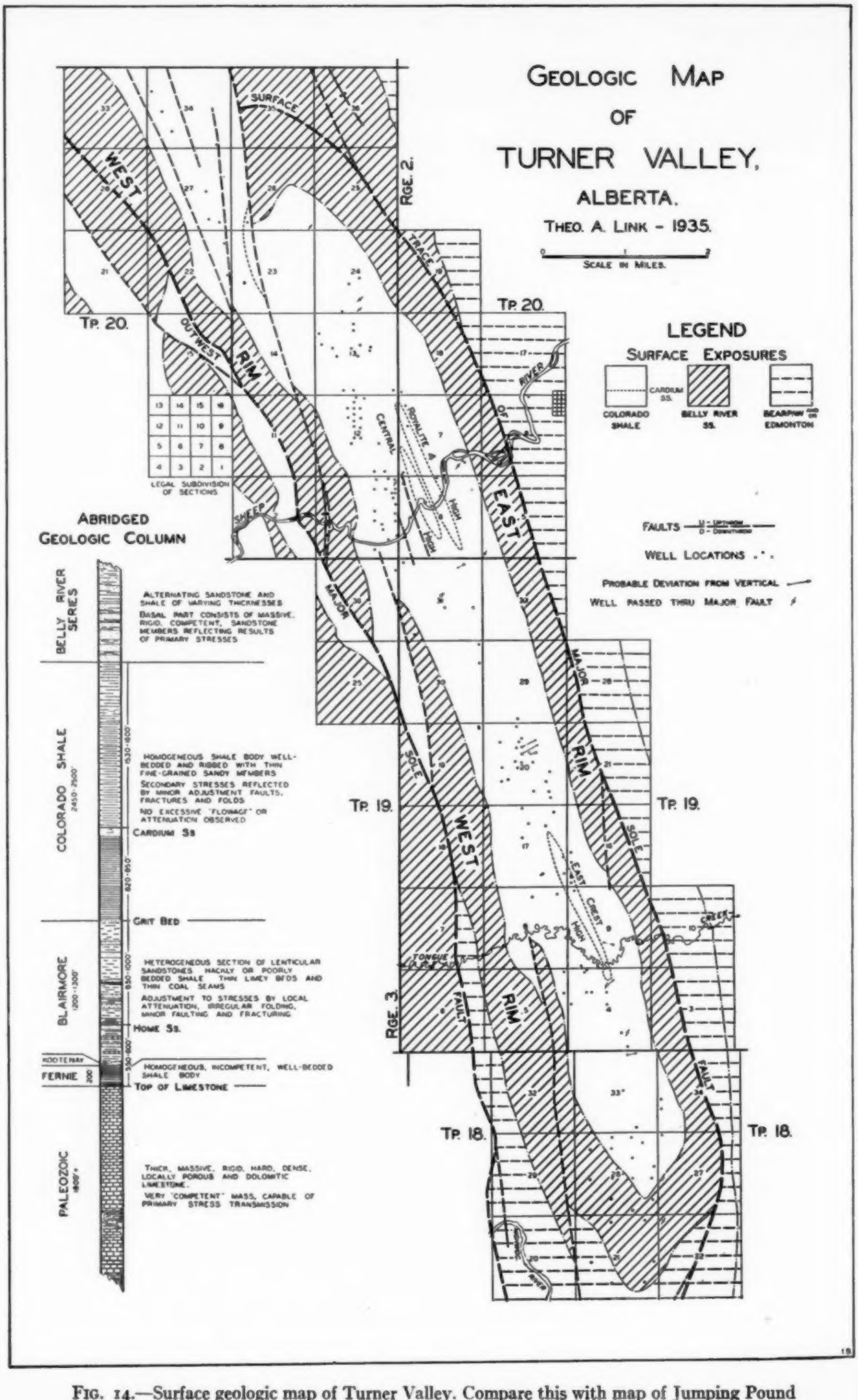

FIG. 14.—Surface geologic map of Turner Valley. Compare this with map of Jumping Pound structure in Figure 15.

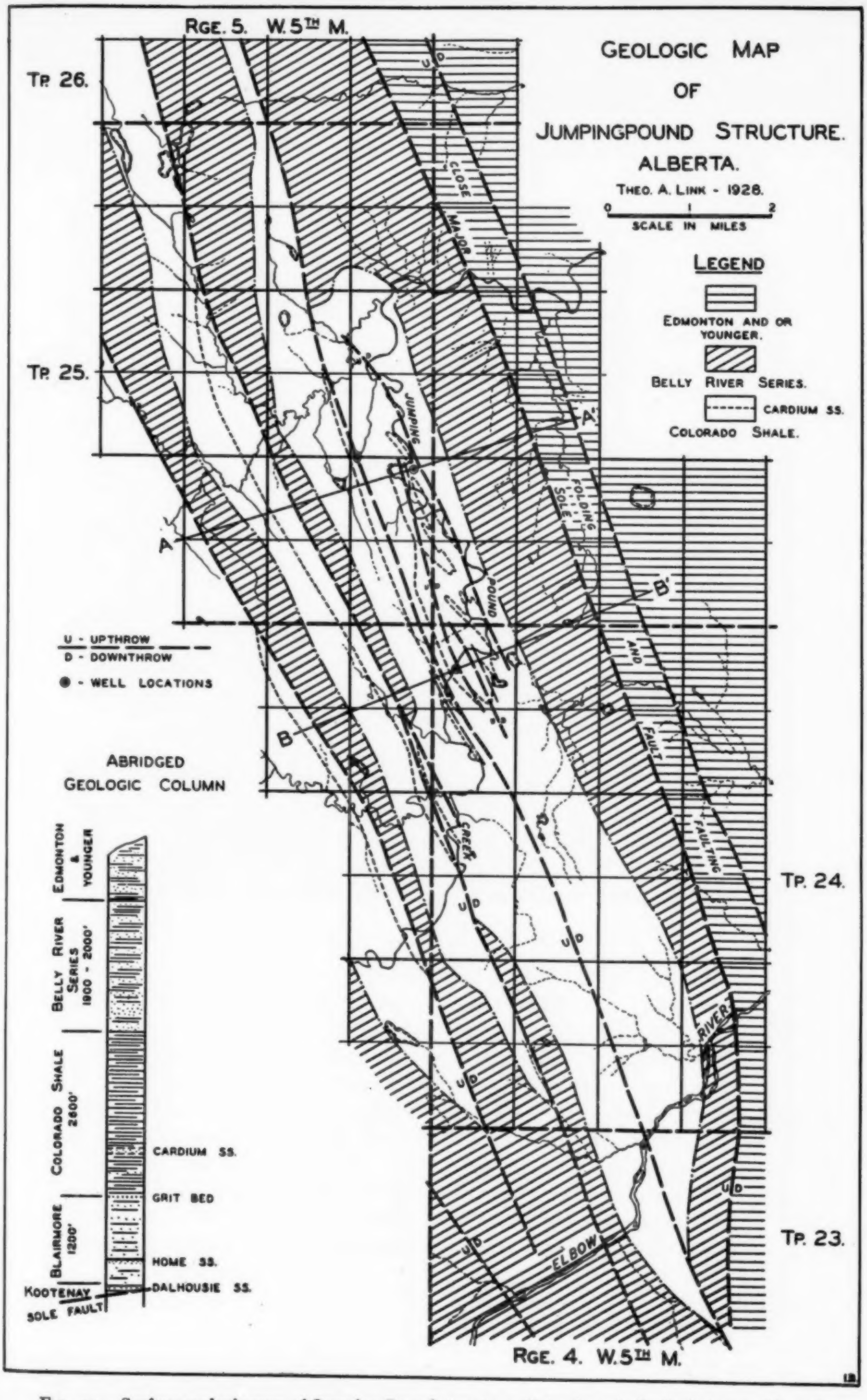

FIG. 15.—Surface geologic map of Jumping Pound structure. Note close similarity between this and Turner Valley structure in Figure 14. Cross sections AA′ and BB′ shown in Figure 18.

the Fisher Mountain sole fault has a sinuous course, which is indicative of a low-angle westward dip. At the surface the fault is closely related to a Kootenay coal seam or series, which apparently acted as a lubricant along the plane of displacement, similar to conditions obtained at the Twin Butte overthrust sheet, and elsewhere in the Foothills area.

The Cottonbelt well No. 1 was located far down the west flank of the uplift with hope of encountering the Paleozoic limestone before passing through the fault, whose existence was recognized. Results obtained at this deep test were, like so many others in the Foothills,

FIG. 16.—Nicoll Ridge forming west Belly River ridge of Jumping Pound structure.

discouraging. The major sole fault was encountered at a depth of 2,680 feet where black shale and coal of Kootenay age were drilled just above the fault plane. Below the fault Belly River beds were encountered to a depth of 3,070 feet, where drilling was suspended.

An examination of the cross section (Fig. 13) reveals a rather complicated structural condition in the Lower Blairmore and Kootenay beds near the eastern limits of this overthrust sheet. An underthrust fault is indicated east of the well site, associated with tight folds. The question of whether or not a decapitated crest of a Paleozoic limestone anticline exists between the Cottonbelt No. 1 location and the surface trace of the fault is not worthy of consideration because the Kootenay

coal series crops out at the surface trace of the fault and was also encountered in the hole above the fault. In the opinion of the writer, the surface geological evidence available on this uplift was sufficient to anticipate a thin overthrust sheet.

The structure is an example of intense minor folding and faulting in a thin overthrust sheet, a condition wholly different from that obtained at the Twin Butte thrust sheet, but prevalent in many others of the Foothills area. The cross section shown in Figure 13 was prepared from a detailed survey of the structure and the well log prepared by the writer.

FIG. 17.—Asymmetrical fold in Colorado shale of Jumping Pound structure.

JUMPING POUND STRUCTURE

The surface geological setting of the Jumping Pound structure (Fig. 15) resembles that of Turner Valley (Fig. 14) more than any other structure in the Foothills area (Fig. 1, locality 12). The structure has a prominent east rim rock formed by Belly River sandstone ledges, and offset west Belly River rim-rock ridges flanked by other thrust faults. The Colorado shale valley between the east and west flanks is denuded down to within 400 feet of the base of this formation, and several minor faulted Cardium sandstone folds are to be observed. The Jumping Pound structure, like Turner Valley, is an outermost fold of the Foothills belt bordering the Alberta syncline and exposing Colo-

rado shale (Fig. 18). In comparing these structures any geologist would be reasonably convinced, on the basis of surface exposures alone, that almost identical conditions should be expected at depth. However, two deep holes drilled on the structure demonstrated the existence of a major sole fault above which the Paleozoic limestone does not exist, as in Turner Valley (Fig. 18). The oldest formation involved in the upthrown side of the Jumping Pound thrust sheet proved to be Kootenay or Fernie beds, and not the Paleozoic limestone, as was reasonable to expect.

At the Bow River No. 1 location (Fig. 18, A) the drill passed from Lower Colorado shale through the sole fault into Upper Belly River beds at a depth of 1,680 feet. At the 3,580-foot mark the Upper Colorado shale was again encountered either by passing through a normal succession of beds or through another sole fault, as shown in the cross section. Drilling was halted at a depth of 5,250 feet in the Colorado shale.

At the second location (Bow River No. 2) drilling commenced below the Cardium sandstone, and the top of the Blairmore was encountered at the shallow depth of 420 feet, which was 460 feet shallower than at any location in Turner Valley (Fig. 18, B). A minor fault repeated this marker at 770 feet, and from that depth to the sole fault a normal section was drilled with showings of gas and oil at several horizons. At a depth of 3,274 feet, the drill passed from Kootenay or Fernie beds through the major fault into Upper Belly River beds, and the hole was abandoned at a depth of 3,530 feet, as indicated in Figure 18, B. The cross section submitted is based on detailed surface geological mapping by the writer and on the well logs.

LOVETT-COALSPUR ANTICLINE

The most northerly deep test made in the Foothills area is located in Ts. 48 and 49, R. 21, West of the 5th Meridian (Fig. 1, locality 17). In 1921 a location was made on this structure east of the crest, but due to drilling difficulties the hole was abandoned and another location was made at or near the surface crest. The two Coalspur tests are located on the northern part of a long, narrow anticline which exposes, on the south, Colorado shale along the axis, but plunges northwestward so that along the south fork of the Embarras River the lowest beds exposed belong to the Brazeau formation, which is, in part, the equivalent of the Belly River series of southern Alberta.

B. R. MacKay[9] surveyed that area, and shows an east-dipping thrust fault on a map and cross section published by the Geological

[9] Cadomin Sheet, Map 209-A, *Geol. Survey of Canada Pub. 2158* (1929), cross section E–F.

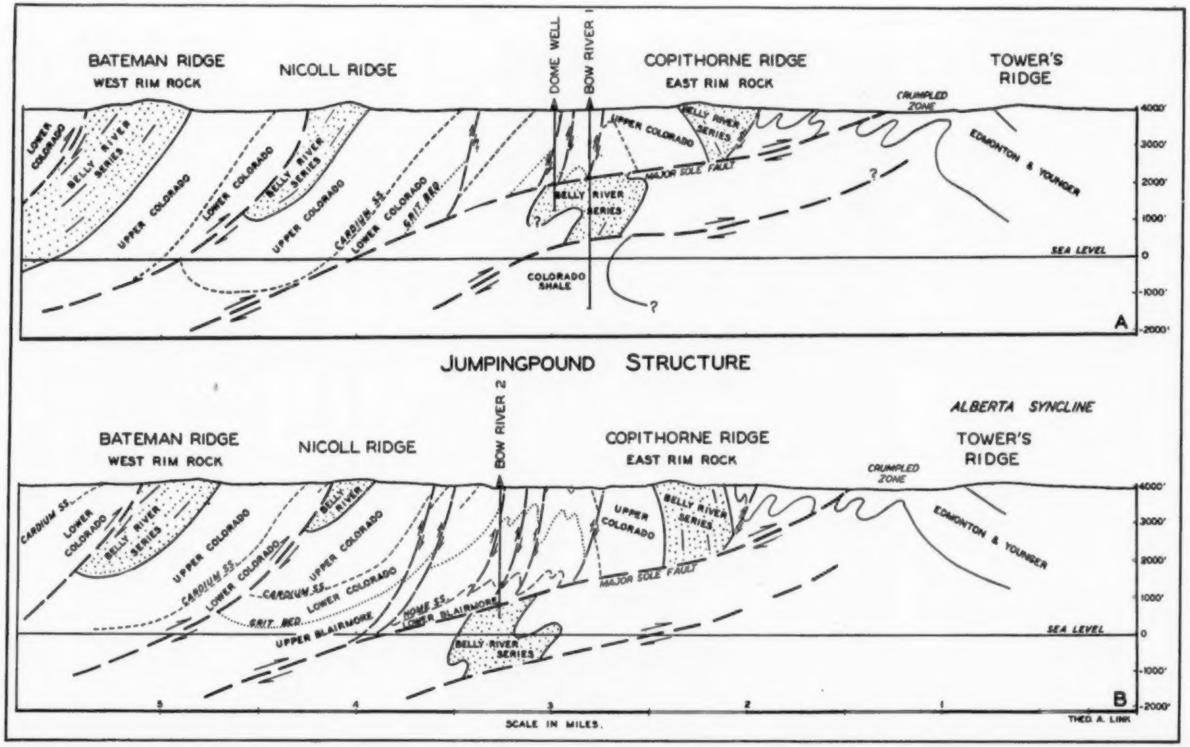

FIG. 18.—*A*. Cross section through northern part of Jumping Pound structure at Bow River location No. 1. *B*. Cross section through north-central part of Jumping Pound structure at Bow River location No. 2. Compare this cross section with those of Turner Valley (Figs. 6 and 7) and note how sole fault lies above Paleozoic limestone in former.

Survey of Canada. His section lies about 2 miles north of the well locations.

The results obtained at the Coalspur location No. 2 seem to fit the facts under the assumption of an east-dipping thrust fault. MacKay[10] is of the opinion that the fault is indicative of *over*thrusting from the *east*, and states:

> The type of folding observed on the outer structures bordering the plains, as at Lovett on Smoky River for seven miles above the junction of Muskeg River, points to the thrust that developed these structures as coming from the plains.

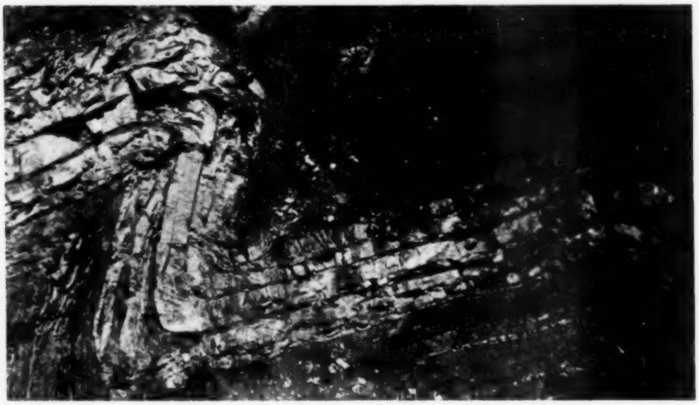

FIG. 19.—A minor fold in northern Foothills showing bending of competent sandstone beds and crumpling of incompetent shale above and below. (Photo by O. B. Hopkins.)

With this view the writer can not agree, but believes that the fault is merely an example of *under*thrusting caused by the same forces which gave rise to the west-dipping overthrusts which are, by far, more numerous.

PALEOZOIC LIMESTONE OUTLIERS IN FOOTHILLS

One other type of Foothills structure which should be mentioned briefly is the Paleozoic limestone outlier, of which there are several, as indicated on the index map (Fig. 1). The better known of these outliers are the following: (1) the Livingstone Range (locality 3); (2) Moose Mountain and Forget-me-not Ridge (locality 11); (3) the Brazeau-Marble Mountain Ridge (locality 13); (4) the Clearwater

[10] B. R. MacKay, "Stratigraphy and Structure of Bituminous Coalfields in the Vicinity of Jasper Park, Alberta," *Bull. of Can. Min. & Met.* 222 (1930), pp. 1306–42.

Ridge (locality 14); (5) the Bighorn Mountains (locality 15); and (6) the Nikanassin-Boule Range (locality 16).

All but one of these limestone outliers are definitely known to be underlain by thrust faults, and have much in common with the other major Foothills structures. They might well be classified as transition types between Foothills and Rocky Mountain structures. On one of these outliers, Moose Mountain, a well (Moose Oils No. 1) was drilled in which a very sulphurous wet gas, similar to the Turner Valley product, was encountered. Drilling commenced in Devonian beds which are stratigraphically below the Turner Valley horizon. Drilling stopped at 2,834 feet, without evidence of repetition. If a low-angle thrust plane underlies the Moose Mountain dome, its surface trace lies far east of the place where the Paleozoic rocks dip beneath the overlying Jurassic and Cretaceous beds. On the east flank of the Moose Mountain uplift a well (Herron Petroleums, Ltd.) was located near the top of the Blairmore beds and was drilled to a depth of 3,220 feet. The Kootenay was reached at 2,030 feet, the Fernie at 2,590 feet, and the top of the Paleozoic limestone at 2,710 feet. Sulphur water was struck in the porous dolomitic zone of the Paleozoic and drilling was suspended before reaching the horizon in the Devonian in which the wet gas was found at Moose Oils No. 1.

The cross section of the Nikanassin Range (Fig. 20, A), is reproduced from B. R. MacKay's[11] paper on the northern coal fields of the Foothills area. In that area the Cretaceous sediments are much thicker than in the outer Foothills belt (Fig. 20, D). Regarding the faulting of this range, MacKay wrote as follows:

> The lower inclination of the fault planes lying immediately in front of the Nikanassin-Boule Range, and that of the Front Range, lying six miles to the southwest, and the more extensive displacement along these, indicate that they were the principal fault-soles along which the major readjustments took place following the general faulting.

The sections submitted by MacKay are all very similar to those prepared by the writer, and indicate the general prevalence of that type of folding and faulting in the northern Foothills belt. There is, however, the general opinion that low-angle thrust faults are not as common as in the southern Foothills area.[12]

Here again deep drilling may throw light on the subject and demonstrate conditions similar to those in the area where data are avail-

[11] B. R. MacKay, "Stratigraphy and Structure of Bituminous Coalfields in the Vicinity of Jasper Park, Alberta," *Canada Min. & Met. Bull. 222* (October, 1930), Fig. 7, pp. 1321–22.

[12] G. S. Hume, "Oil and Gas in Western Canada" (2nd ed.), *Geol. Survey of Canada Econ. Geol. Ser. 5, Pub. 2128* (1933), p. 30.

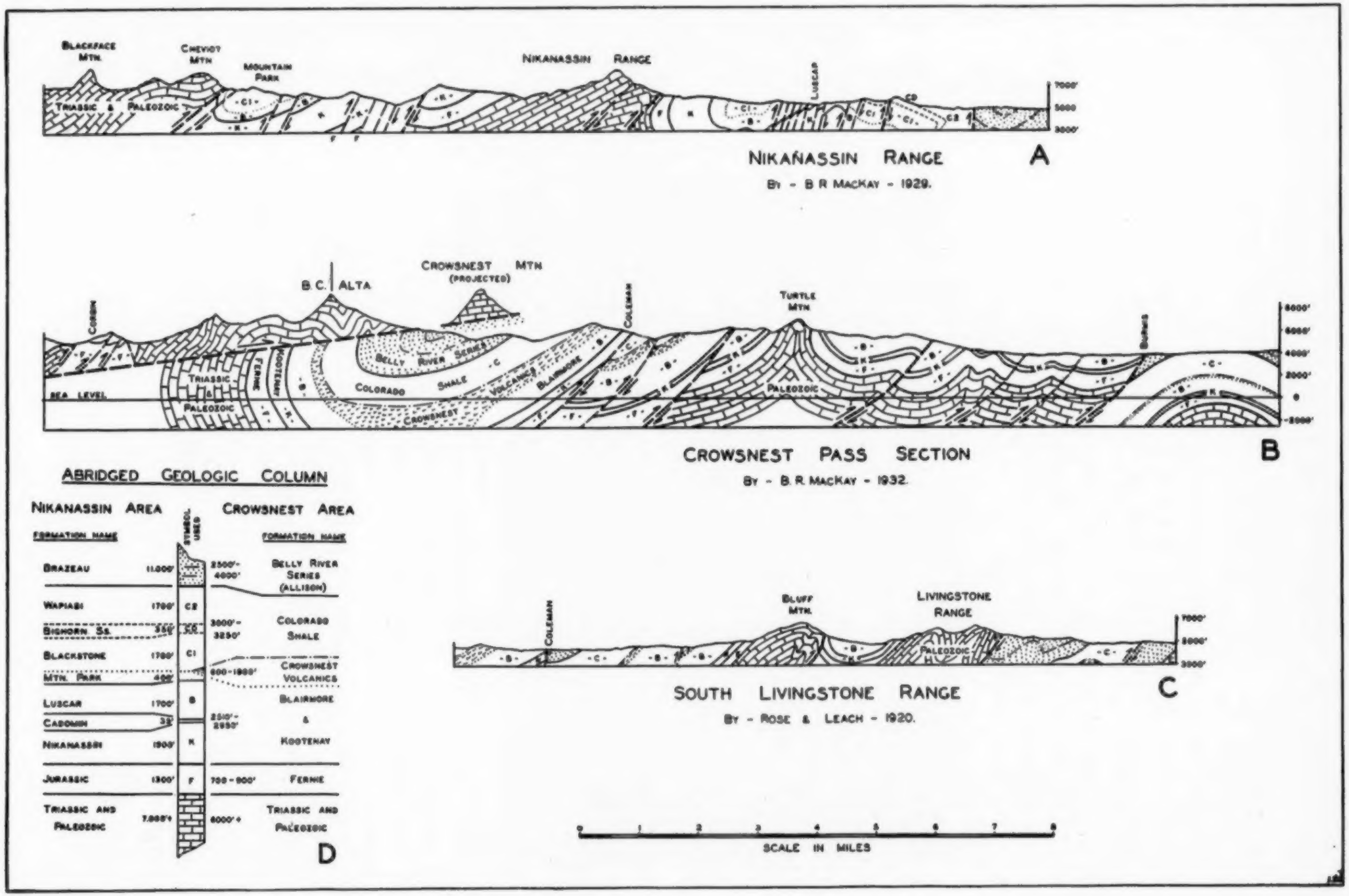

FIG. 20.—*A*. Cross section of Nikanassin-Boule limestone range by B. R. MacKay. Note similarity between this and other Foothills structures. *B*. Cross section showing Crowsnest Mountain outlier on low-angle overthrust fault and Rocky Mountain structure by B. R. MacKay. *C*. Cross section of Livingstone limestone range by Rose and Leach with additions. This range appears to be a large-scale Turner Valley type denuded to Paleozoic limestone. *D*. Geologic column for Crowsnest and

able. The Upper Cretaceous beds are, in general, much thicker and more competent and possibly more conducive to open folding with lesser tendency to thrust faulting.

A cross section from Rose and Leach[13] through the Livingstone Range or outlier north of the Crowsnest Pass is shown in Figure 20, C. This section shows the similarity between these limestone outliers and other Foothills structures where erosion has not exposed the Paleozoic limestones. The presence of underlying thrust faults is definitely established, but the angle of dip is a matter which can not be decided

FIG. 21.—Looking south across South Twin Creek at Paleozoic anticlinal uplift of North Livingstone Range.

except by inference. The writer is inclined to believe that relatively low-angle thrust faults are the rule, and since the Paleozoic limestone is shown to be fairly tightly folded and also faulted, the same conditions might also be obtained in the northern Foothills in spite of greater competency in the Upper Cretaceous beds.

An interesting section by MacKay[14] is submitted as Figure 20, B, showing the relatively low-angle thrust fault of the Crowsnest Mountain outlier, which is similar to Chief Mountain of northern Montana.

[13] B. Rose and W. W. Leach, "Blairmore Map Area, Alberta," *Geol. Survey of Canada Pub. 1584* (1920), Scale, 1 inch = 1 mile.

[14] B. R. MacKay, "Geology and Coal Deposits of Crowsnest Pass Area, Alberta," *Geol. Survey of Canada Summary Report* (1932), Pt. B, Fig. 6.

FIG. 22.—Looking south at west flank of North Livingstone Range limestone outlier as viewed from Livingstone River near Twin Creek.

FIG. 23.—Looking north at Crowsnest Mountain west of Blairmore. Overthrust Paleozoic limestone outlier resting on Cretaceous beds.

It is highly probable that this fault is the northward continuation of the Lewis overthrust to be discussed later in this contribution (locality 4, Fig. 1).

MINOR STRUCTURES IN FOOTHILLS

Space will not permit the description of the various types of minor folds and faults observed in the Foothills belt of Alberta. Excellent sections reveal almost all conceivable types and sizes of folds and faults. The types of minor structures are dependent upon the nature of the formations in which they were developed. There are simple, symmetrical or asymmetrical anticlines, faulted or unfaulted; overturned folds and underfolds; flat-topped and sharp-crested (roof type) folds; anticlines with competent beds between which shales

FIG. 24.—Minor, low-angle thrust fault in Blairmore series on South Sheep River close to Rocky Mountain escarpment.

have been crushed and squeezed; fan-folds with in-dipping faults on their flanks, and anticlinoria flanked by out-dipping faults. Minor fault wedges due to in-dipping faults are common, as are their complementary structures. Tension fissures at the crest and in the trough of folds in brittle beds may be observed. Decapitated minor anticlines and sheared-off synclines are also common features. Examples of parallel folds, similar folds, or hybrids of these abound everywhere. It is difficult to evaluate the real significance of this diversity of structure in trying to decipher the major features, and in many cases it is a matter of "not being able to recognize the forest because of the trees." Commonly what appears to be only a minor feature proves

FIG. 25.—Tight fold of Cardium sandstone in Colorado shale along Elbow River above Bragg Creek.

FIG. 26.—Underfolded, sharp-crested anticline involving Grit bed of Blairmore series along Sheep River, about 4 miles west of Turner Valley.

to be a very insignificant manifestation of a major feature. The reverse is also commonly the case.

Transverse faults are conspicuous by their absence, although minor ones of several feet displacement have been observed. In connection with this subject it is of interest to call attention to a particularly narrow, sharp-crested, locally overturned and faulted fold involving the Grit bed at the top of the Blairmore series. This narrow and faulted fold, as observed along Sheep River, lies on the west flank of the Waite Valley-Highwood uplift, and is only 250–400 feet wide,

FIG. 27.—Coxcomb ridge of Cardium sandstone lying between two forks of Fallentimber Creek in Inner Foothills area near Red Deer River.

but can be definitely traced a distance of 14 miles. Along its entire length there is no evidence of transverse faulting. This narrow structure with the Grit bed core appears on Figure 7 at the extreme left directly under the space between the words "Waite Valley." It is also shown in Figure 6 along the Highwood River section where the Warner Oils location is shown on the illustration. There is a definite *grain* in the Foothills structure practically undisturbed by transverse flaws or tearing.

There are examples of narrow Cardium sandstone folds which show overturning on one side and, where traced along the axis, underfolding on the opposite side, thus giving rise to a twisted or "cork-

screw" axial plane. The Millarville sole fault, previously described[15] as overlapping the north end of the Turner Valley thrust sheet, is interpreted as a hinge thrust fault which begins in a steep anticline at its southern extremity and develops into a thrust fault of increasing displacement in a northerly direction.

An interesting minor fault, established by surface exposures and diamond drilling, is to be noted on the cross section of the Twin Butte overthrust sheet (Fig. 2, A). On the cross section at the immediate right of core hole 5 is shown an overthrust fault within the Lower Colorado shale which is turned back on itself. Details of this are shown in Figure 28. This might be classified as a "pseudo-discoidal" fault,[16] similar to the one produced by experiment as illustrated in Figure 29.

OTHER FOOTHILLS STRUCTURES AND GEOPHYSICAL PROSPECTING

There are several other Foothills structures not described where deep tests have given the necessary data to construct reasonable cross sections. However, these would be mere variations of those described in this contribution with only minor differences in detail. On several structures where drilling is now being carried on, subsurface interpretations may be known shortly. There are still others which, from surface data, appear to be very reasonable prospects from an oil or gas production view. The existence of sole faults underlying these structures is known, but whether or not the Paleozoic limestone is involved in the thrust sheet is a matter which can be established only by drilling on well chosen sites. If geophysical prospecting continues to advance, some method may be devised whereby such determinations could be made before drilling. The writer believes that the ultimate correct interpretations and mapping of the Foothills and similar areas must await some geophysical method to be developed in the future which could be used in conjunction with detailed surface geological mapping.

One may venture the suggestion that it might be possible to commence drilling in relatively younger beds on an unfavorable structure of a surface thrust sheet which overlies another sheet involving the Paleozoic limestone, and thus reach the objective where least expected. The various cross sections submitted show clearly that the stratigraphic displacement along the major sole faults is not neces-

[15] Theodore A. Link and P. D. Moore, "Structure of Turner Valley Gas and Oil Field, Alberta," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 18, No. 11 (November, 1934), pp. 1423 and 1450.

[16] Theodore A. Link, "Relationship between Over- and Under-Thrusting as Revealed by Experiments," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 12, No. 8 (August, 1928), p. 845 and Fig. 33.

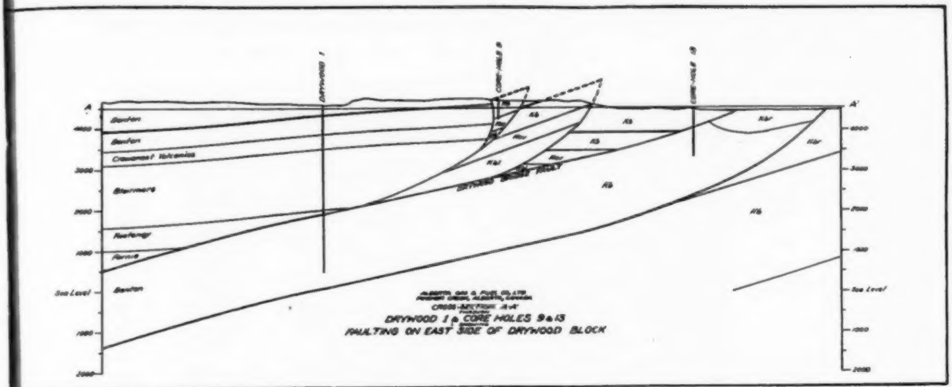

FIG. 28.—Detail of Twin Butte overthrust sheet near Drywood location No. 1, showing "discoidal" fault developed about 1 mile east of well location. (By Luis E. Kemnitzer.)

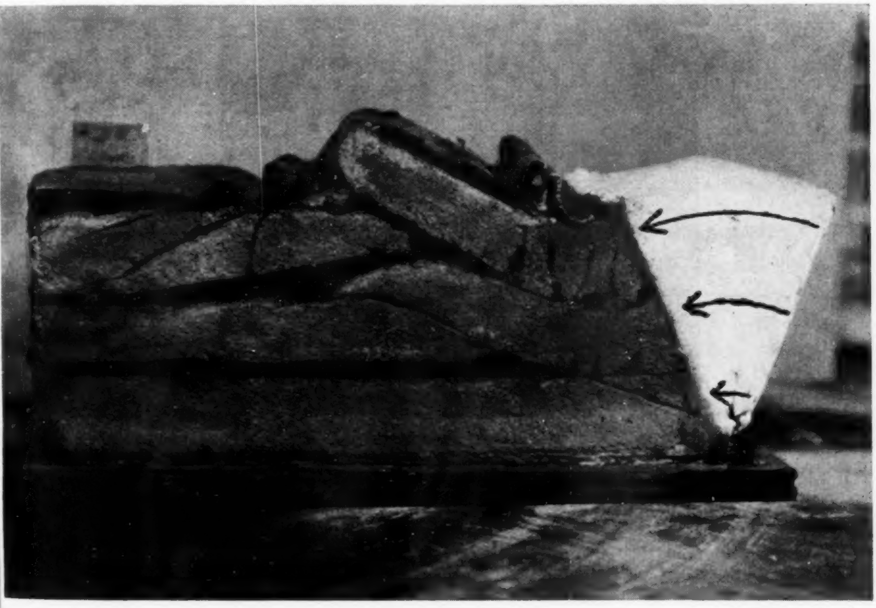

FIG. 29.—Apparent discoidal fault developed by deflection of low-angle overthrust fault by tension fissure or fault dipping in opposite direction. Arrows on pushblock indicate direction of pressure application.

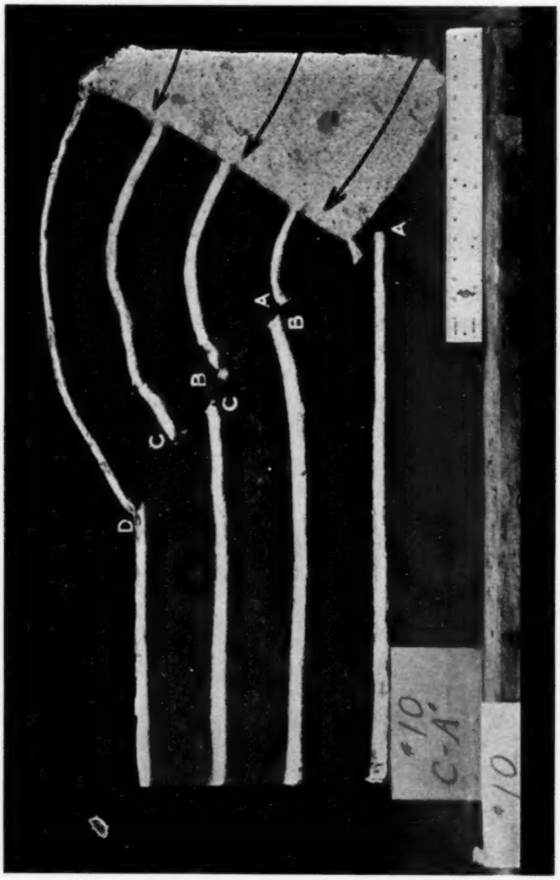

FIG. 30.—Artificially produced overthrust fault showing decrease of displacement upward away from source of compression. Arrows on pushblock indicate method of pressure application. Bed *A* is displaced 6 cm.; bed *B*, 3.6 cm.; bed *C*, 2.3 cm.; and bed *D*, 0.6 cm.

sarily an index of the actual amount of shift, and that the structures beneath the sole fault do not conform to those above.

For the benefit of those not familiar with the Foothills area it is in place to emphasize the fact that outcrops are plentiful. Long, narrow ridges of individual formation members can be traced for miles from one transverse stream to another, as in Figure 27, and topographic expression of surface structure is well developed. One is usually not hampered by lack of data, but the contrary is the rule. There is no difficulty in recognizing the major stratigraphic subdivisions throughout the Foothills area.

STRATIGRAPHIC RELIEF WITHIN FOOTHILLS BELT

One significant feature with respect to the Foothills is the extremely small stratigraphic relief in comparison with the width of the belt. With several exceptions of Paleozoic outliers, the true Rocky Mountain front or the western border of the Foothills is delineated by a Paleozoic or older escarpment, while the eastern edge of the Foothills ends abruptly against the Alberta syncline where Cretaceous rocks are faulted against, or dip beneath, Tertiary beds. There are few places in the Foothills area south of Red Deer River where beds younger than Bearpaw or Edmonton may be observed. The total section from the top of the Paleozoic limestone to the top of the Bearpaw shale varies from 6,000 to 8,000 feet, or 1.5 miles. (These figures are only approximate, but are not more than 15 per cent in error.) Thus, while the average width of the southern Foothills belt is 18 miles, the average stratigraphic relief is less than 1.5 miles. There is no doubt that the Foothills belt was, before being compressed and telescoped by faulting, at least 40 miles wide. This very insignificant stratigraphic relief could not exist if major high-angle thrust faults were more common than the low-angle type described in this contribution. This consideration may be of some value for other areas unexplored by deep drilling, where well developed surface structures exist.

Exclusive of the several limestone outliers, the greatest single *stratigraphic* displacement observed at the surface in the southern Foothills is generally less than 3,000 feet. The Fisher Mountain overthrust sheet described in this contribution is an example of a comparatively great stratigraphic displacement observed at the surface. As stated previously, Kootenay beds are in contact with Upper Colorado shale at the surface trace of this fault, which amounts to a stratigraphic displacement ranging from 2,000 to 3,000 feet. It is interesting to note that where the drill passed through this thrust sheet the stratigraphic displacement is greater, since Kootenay beds were found

faulted over the Belly River series at the Cottonbelt well location. Thus the displacement increases at depth, as is also the case in Turner Valley, and all other thrust sheets where data are available. This bears out the writer's[17] observation that "primary or major overthrust faults should show a progressive *decrease* in displacement *upward* toward the surface, away from the source of stresses." An excellent example of this principle produced experimentally is illustrated in Figure 30.

LEWIS THRUST AND TWIN BUTTE SALIENT

An examination of the index map (Fig. 1) reveals a decided "bulge" or "salient" in both the Rocky Mountain front and the Foothills belt where the Twin Butte thrust sheet is located. The decided northwest swing of the Rocky Mountain front is reflected in the Twin Butte thrust sheet and all Foothills structures lying east of it. There is no surface evidence of a transverse or tear fault along this sudden change in strike of the Foothills, and speculation regarding its cause is of interest to all those who have worked in the area. In a previous contribution the writer[18] presented experimental data which may have some bearing on this subject. In discussing the causes of *en échelon* folds and arcuate mountains the following conclusions were reached.

1. *En échelon* folds and arcuate mountain systems are polygenetic.
2. They may be due to a lateral variation of tangential forces, which amounts to rotational compression in the horizontal plane. The manner in which this may be accomplished is also variable.
3. They may be caused by non-rotational forces operative in the horizontal plane against sediments which have a decided lateral variation in plasticity, rigidity or competency, giving rise to variable stress-transmission.

These conclusions may also be applied to the development of salients and recesses in mountain systems, such as the Lewis overthrust salient and the Crowsnest Pass recess.

The ultimate cause for the development of the rigid Lewis overthrust plate or sheet may have been due to a localization of stresses along that part of the Rocky Mountain front. As already pointed out, the rigidity of the Twin Butte overthrust sheet was derived from the formerly overlying Lewis thrust sheet. In consequence, the transmission of stresses had to be farther eastward along the Foothills belt, as is indicated on the map (Fig. 1, localities 1 and 1, A). North

[17] Theodore A. Link, "Individualism of Orogenies Suggested by Experimental Data," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 4 (April, 1931), p. 403.

[18] Theodore A. Link, "*En échelon* Folds and Arcuate Mountains," *Jour. Geol.*, Vol. 36, No. 6 (August–September, 1928), pp. 526–38.

of this "salient," along the Crowsnest River, is the complementary "recess," where the folding and faulting within the Foothills area appears to be much more intense than on the Twin Butte sheet. It is significant to note that along the Crowsnest River the Rocky Mountains are not one relatively flat thrust plate of pre-Cambrian and Paleozoic rocks, but are broken up into more numerous overturned and faulted folds and higher-angle fault blocks, and thus the transmission of stresses eastward was limited (Fig. 20, B).

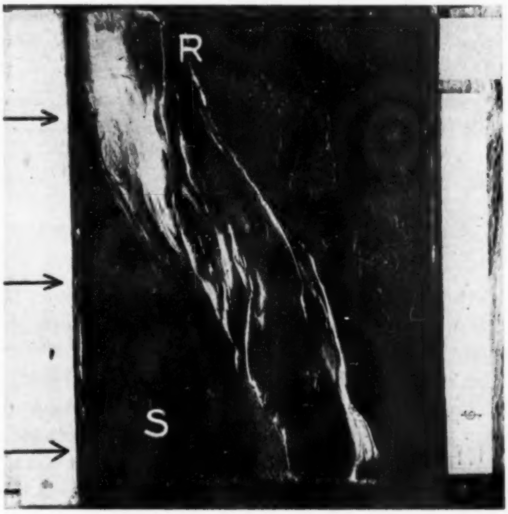

FIG. 31.—Top or surface view of "salient" (*S*) and "recess" (*R*) produced in artificial sediments by application of non-rotational compression from left as indicated by arrows. Basal layer was made more rigid or competent in lower left corner under *S*, thus causing transmission of stresses beyond center of model, while in upper left corner folding and faulting occurred directly in front of push block.

Figure 31 is a top view of an experiment in which a condition similar to the one already described was effected artificially. On the lower left side in the lower layer more rigidity was imparted to the artificial sediments. Equal pressure was applied, as shown by the arrows, but the transmission of stresses was greater through the more rigid part of the lower layer, thus giving rise to a well developed salient (*S*) and recess (*R*). In applying this explanation to the Lewis overthrust salient and the associated Twin Butte salient of the Foothills belt, it is not necessary to postulate a change in direction of forces

operative. It is highly probable that the total amount of shortening of beds in the Lewis and Twin Butte salient is no greater than that of the Crowsnest recess. In the former fewer faults and folds occur, but the displacement along the larger faults is greater, and the sum total is probably of the same magnitude.

From Crowsnest River northward the eastern edge of the Foothills belt runs essentially due north. Turner Valley appears to be another salient of the Foothills belt, as indicated on the map (Fig. 1, locality 8). This minor salient may have been caused by a lateral variation of tangential forces or by unequal transmission of these forces because of unequal lateral competency of the formations involved. Another "bulge" along the eastern margin of the Foothills is to be noted between Red Deer and Athabasca rivers. In this part of the Foothills belt are located the greatest number of Paleozoic limestone outliers which suggest a localization of primary stresses along that salient.

RELATIONSHIP BETWEEN FOOTHILLS AND ROCKY MOUNTAIN STRUCTURE

The prevalence of extremely low-angle thrust faults in the Foothills, and the striking resemblance of the Twin Butte sheet to the Lewis overthrust sheet in the Rocky Mountains, emphasizes very strongly the close structural relationship between the two physiographic provinces. One is tempted to suggest that low-angle thrust sheets might be more numerous in the Rocky Mountains than is commonly supposed. Furthermore, it is highly probable that the most westerly or first formed overthrust fault planes were folded and re-faulted. This suggests reconsideration of the possibility that the Tertiary and Mesozoic-floored valley of Flathead River at the west of the Lewis and Clarke ranges may be a "window" surrounded by the warped or folded Lewis overthrust fault (Fig. 1). This possibility was suggested by the writer at the San Antonio, Texas, meeting of the Association in March, 1931. At the request of the late Sidney Powers the chapter dealing with that subject was condensed to a few short statements, the three cross sections were omitted, and only the underthrust hypothesis for the Sage Creek fault was presented in the published paper on the subject, "Oil Seepages in Belt Series of Rocky Mountains near International Boundary."[19]

Figure 32 shows the three cross sections illustrating the three hypotheses presented at the San Antonio meeting. The details of the

[19] Theodore A. Link, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 8 (August, 1932), p. 795.

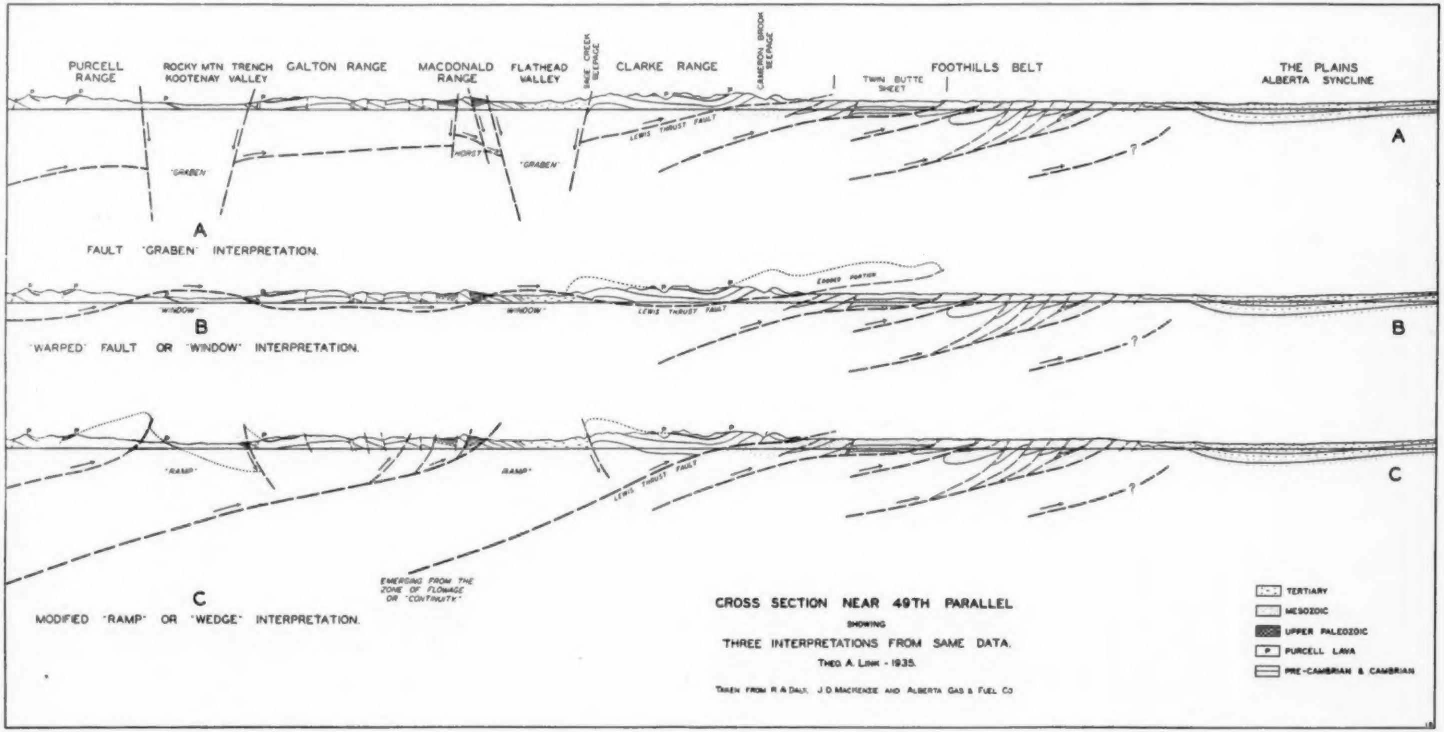

FIG. 32.—Cross section along International Boundary showing three interpretations from same data of Rocky Mountain Trench, Flathead Valley, and Lewis overthrust.

Foothills belt have been altered to fit the most recently gathered data. As previously stated, interpretation *B*, the warped fault or "window" hypothesis, may be more nearly correct than *C*, the underthrust interpretation. The same hypothesis might also be applied to the Rocky Mountain Trench, which is similar to the Flathead Valley. On this hypothesis, the Lewis overthrust has a displacement of at least 44 miles. The writer can not convince himself that the Rocky Mountain Trench actually is a "window" of the Lewis thrust fault or possibly that of a previously developed one above the former. However, the possibility of ascribing such an explanation to the Flathead Valley Trench is worthy of serious consideration. In this case, the evidence supporting such an interpretation would also have to be clear-cut and undeniable before it would be accepted. Excepting for the Lewis overthrust in the Waterton Lakes area, no major faults observed in the Rocky Mountains *appear* to be of the extreme low-angle type, as may be deduced from the present literature. This, however, is not conclusive, because practically all publications on Foothills geology prior to 1930 gave little, if any, indication of the great prevalence of the extremely low-angle type of faulting and the relatively thin thrust sheets.

Crowsnest Mountain (locality 4, Fig. 1 and Fig. 20, B) is, according to MacKay,[20] an outlier of such low-angle faulting, which may be the northward continuation of the Lewis thrust sheet. More detailed information may reveal other examples. Deep drilling in the Foothills area has revealed the true nature of conditions in that area, but such information may never be obtained west of the Rocky Mountain front. The generalized cross section shown at the top of the Index Map (Fig. 1) indicates the writer's present conception of the structural relationship between the Rocky Mountain Trench, the Rocky Mountains, the Foothills, and the Alberta syncline. The vertical and horizontal scale are the same on this section, as in all cross sections figured in this contribution. The generalized cross section was drawn as closely to scale as possible with the object in view of showing how relatively thin the folded and faulted rocks of the Rocky Mountain and Foothills belt actually are in comparison with their lateral extent.

METAMORPHISM, CARBON RATIOS, AND SEEPAGES

During the informal discussions of this contribution when presented at Houston and San Antonio, Texas, the writer was asked about several topics not dwelt on, but regarding which those not

[20] B. R. MacKay, "Geology and Coal Deposits of Crowsnest Pass Area, Alberta," *Geol. Survey of Canada Summary Report* (1932), Pt. B, pp. 21–67 and Fig. 6.

familiar with the area seemed concerned. Several were interested in carbon ratios, others asked about oil and gas seepages, while some wanted data regarding metamorphism of the rock section.

None of the limestones or dolomites observed by the writer in the Paleozoic outliers of the Foothills, the eastern range of the Rocky Mountains, and in cores obtained by drilling in Turner Valley or other structures, shows any suggestion of being marbleized. The Colorado shale of the Foothills is harder and more rigid than in the Plains area but there is no suggestion of slate or slaty cleavage development. The same applies to the Fernie shale. The sandstones of the Belly River series, the Blairmore and the Kootenay beds have not reached the true quartzite stage, but there are several members in the lower formations, interbedded with normal sandstones, which might be classified as approaching quartzite. (Probably due to static metamorphism.)

For excellent discussions, but with diametrically opposite conclusions on carbon ratios in western Canada, the reader is referred to contributions by Jones[21] and Hume.[22] The data given herewith are taken from I. W. Jones, who reports that the carbon ratios of the Kootenay coals (Lower Cretaceous) range from 64 to 89 per cent. The Belly River coals (Upper Cretaceous) of the Foothills range from 55 to 63 per cent, while Edmonton coals (uppermost Cretaceous) vary from 55 to 60 per cent. Regarding the entire problem, Jones[23] remarks:

> Considering the region broadly, it is true that the highest carbon ratios are found in the Kootenay coals of the mountains. But, on examining that whole area east of the mountains, a veritable jumble of carbon ratios is perceived.

According to Thom's[24] classification, no true anthracite is being mined in either the Foothills or the Rocky Mountains, and light oils and gas might, on the basis of the carbon-ratio theory, be encountered anywhere in the Foothills and the eastern range of the Rocky Mountains. It seems that the large number and great displacement of overthrust faults relieved the pressure sufficiently to prevent metamorphism of the coals into anthracite. As already pointed out, it appears that the coal beds themselves were, to a great extent, responsible for easier relief of stresses by acting as lubricants.

[21] I. W. Jones, "Carbon Ratios as an Index of Oil and Gas in Western Canada," *Econ. Geol.*, Vol. 23, No. 4 (June–July, 1928), pp. 353–80.

[22] G. S. Hume, "Carbon Ratios of Coal as an Index of Oil and Gas Prospects in Western Canada," *Trans. Can. Inst. Min. and Met.*, part of Vol. 30 (1927).

[23] I. W. Jones, *op. cit.*, p. 365.

[24] W. T. Thom, Jr., *Petroleum and Coal*, Princeton University Press (1929), p. 31.

According to David White's[25] posthumous publication, the "dead-line" or the "carbon-ratio limit" lies between 65 and 70 per cent fixed carbon, and therefore the Foothills and Rocky Mountain region of Alberta lies close to this "zone of extinction." The writer hopes to deal more fully with this problem in a later contribution.

Oil or gas seepages are not common, though present in the Foothills area. Gas seepages are more numerous than oil seepages. They are usually found along fault planes or zones. The most interesting oil seepages are those found within the Rocky Mountains in the

FIG. 33.—Gas seepage along bank of Sheep River in central part of Turner Valley a few yards from Royalite well No. 1.

Lewis overthrust salient in and near Waterton Lakes Park.[26] The oil from the seepages along Cameron Brook is heavier than that obtained in Turner Valley, in spite of the fact that the former comes from the Rocky Mountains, and the latter from the outermost Foothills structures. A gas seepage observed along Sheep Creek in Turner Valley is directly responsible for the early drilling on that structure (Fig. 33).

The absence of igneous intrusives in the eastern Rocky Mountains and the Foothills belt seems to indicate the relative shallowness of

[25] David White, "Metamorphism of Organic Sediments and Derived Oils," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 19, No. 5 (May, 1935), p. 608.

[26] Theodore A. Link, "Oil Seepages in Belt Series of Rocky Mountains near International Boundary," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 8 (August, 1932), pp. 786–96.

this zone of folding and faulting. The absence of excessive heat during this orogenesis, other than that caused and generated by the compressive forces themselves, is attested by the lack of extreme metamorphism of the sediments.

SUMMARY

The several types of individual structures described and illustrated in this contribution are by no means the most prevalent in the Foothills of Alberta. The ones described were chosen because of the data obtained in the deep tests made on the structures, and the detailed surface information available. They represent what petroleum geologists regarded as the most promising appearing structures for oil or gas, based on the available surface data. Simple, westward dipping fault blocks are, by far, the most prevalent type, but have been avoided in drilling for oil, and wherever anticlinal conditions exist, or appear to exist, the petroleum geologist has become interested. The fact that so many, possibly all, of this type are underlain by relatively *low-angle* thrust faults was not demonstrated until recently. The existence of thrust faults was denied by a few geologists, and the extremely low angle of dip of the faults and their warped or folded condition were not established until well chosen deep test holes made such data available.

At the present writing the real significance of Foothills thrust sheets can not be appreciated to its full extent because of too meager information. Any structure examined, no matter how favorable it may appear at the surface, must be considered with its possible "uninvited step-child," the underlying sole fault. It may or may not lie at a shallow enough depth to cut off the Paleozoic limestone or known producing horizon before it is reached. As pointed out in describing the various structures, it is, in many places, possible to observe crumpled zones and individual faults lying east of a favorable appearing structure, but the angle of dip is rarely determinable. As a matter of fact, where actual fault planes are exposed to observation, the dips are almost invariably high.

In a few faulted regions, as at the Fisher Mountain, Twin Butte and the northern part of the Outwest fault, the sinuous topographic expression of the faults is sufficient evidence to suggest relatively low-angle faulting and thin thrust sheets. At Rice Creek and Jumping Pound the crumpled zones lying on the east were observed to run very straight, with no suggestion of flat-lying sole faults. The almost vertical dips in the Colorado shale on the east flank of the Outwest structure along Sheep River, are also highly suggestive of the rela-

tively shallow underlying thrust fault. On the Mill Creek structure west of Pincher Creek, the overturned Blairmore beds on the east flank of that structure and the surface exposure farther east, where Colorado shale is faulted against westward dipping Belly River beds, might be regarded as ample suggestion that the underlying fault would be encountered at a relatively shallow depth.

Underthrust faulting and underfolding as observed along the Highwood River and on the Pekisko structure are highly suggestive of secondary adjustments subsequent to or during the major movements along the underlying major sole fault. The intensity of minoı folding and faulting and the presence or absence of relatively flat beds do not give clues as to the angle of dip of the underlying sole fault. The Fisher Mountain overthrust sheet is a highly faulted and tightly folded unit, while the Twin Butte thrust sheet is essentially a flat-topped anticlinal arch. Both are underlain by extreme examples of low-angle thrust faults. As pointed out, the Twin Butte thrust sheet remained essentially undisturbed because of the overlying rigid Lewis thrust sheet. In the case of Fisher Mountain no evidence of a formerly overlying rigid sheet is available, and therefore the secondary folding and underthrusting must have taken place subsequent to the major sole fault, but before the growth of the later developed deeper-lying thrust fault had advanced sufficiently to relieve all stresses on the two contiguous sheets.

For the sake of emphasis, the rôle played by coal beds as lubricants along major sole faults is again mentioned. The observation of faults at the surface in juxtaposition with coal is everywhere suggestive of low-angle faulting.

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* In G. S. Hume's "Oil and Gas in Western Canada," a more complete bibliography for all the areas discussed in this report is found. Recent maps by Hume and MacKay, published by the Geological Survey of Canada, cover a great number of the structures discussed.

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VOL. 19, NO. 10 (OCTOBER, 1935), PP. 1472-1507, 3 FIGS.

GEOLOGIC STRUCTURE OF SOUTHEASTERN UTAH[1]

A. A. BAKER[2]
Washington, D. C.

ABSTRACT

Southeastern Utah, lying within the Colorado Plateau, is characterized by several types of structural features, including (a) huge asymmetrical upwarps, (b) domes associated with laccolithic intrusions, (c) the southern edge of the Uinta Basin structural depression, (d) a north-trending zone of normal faults at the west edge of the plateau, and (e) a group of numerous folds, faults, and faulted folds that are found in a limited area near Moab. Folding has occurred in the region several times since the end of the Mississippian, but the principal deformation that is reflected in the structure of the surface rocks took place at the end of the Cretaceous or early in the Tertiary and was therefore related to the Laramide orogeny. The large domical uplifts have a northerly trend and are strongly asymmetric, with the steep limb toward the east; they were formed at the end of the Cretaceous, possibly as a reflection in the surface rocks of more or less vertical uplifting along deep-seated reverse faults. The group of numerous smaller folds, faults, and faulted anticlines in the part of the region near Moab also is believed to have been formed near the end of the Cretaceous; the deformation is obviously related to the presence of the plastic salt-bearing beds of the Pennsylvanian Paradox formation beneath the surface rocks, because the structural features of this type near Moab are typically developed only within the area underlain by the Paradox formation and because the salt-bearing beds have been intruded into the overlying rocks at the crests of some of the folds. Events in the Tertiary structural history of the region include the intrusion of igneous rocks in four isolated mountain groups, the downwarping of the Uinta Basin, and the development of the zone of normal faults at the west edge of the plateau; it is not possible to determine the order of these events, or to determine whether they represent different modes of expression of one period of crustal disturbance.

INTRODUCTION

The area in southeastern Utah described in this paper includes most of the northern part of the Colorado Plateau. The relatively simple structure of open folds and normal faults of this area contrasts strongly with the more intense folding and faulting in the Great Basin on the west and Rocky Mountains on the east. Because of the relative simplicity of its structural features, and because of the existence within it of broad expanses in which the rocks have low structural relief, there has been a natural tendency to consider the Colorado Plateau as a comparatively stable or inert area during the deformation of the adjoining regions. Although in a general way this is true, the sedimentary rocks of the plateau in southeastern Utah have

[1] Manuscript received, July 21, 1935. Read before the Association at the Wichita meeting, March 23, 1935. Published by permission of the director of the United States Geological Survey.

[2] Geologist, United States Geological Survey.

nevertheless been deformed at several epochs in their history and are now folded into numerous anticlines and synclines that range in size from small wrinkles of slight structural relief to large folds with thousands of feet of relief and with an areal extent of hundreds or even thousands of square miles. The total structural relief in the area is nearly 15,000 feet; along certain monoclines the local relief ranges from 4,000 to 8,500 feet in distances of 3 to 10 miles and in a few places the strata are nearly vertical. Normal faults with displacements of several thousand feet are numerous, although they are concentrated in certain parts of the region.

The information upon which the map is based has been obtained largely from reports of the United States Geological Survey recently published or now in preparation.[3] After the compilation of the map was well under way, the writer made a brief reconnaissance survey of several areas for which satisfactory structural data were not available. In addition, several oil companies and consulting geologists have furnished structure contour maps of local areas. The writer wishes to express his appreciation for information supplied by the Stanolind Oil and Gas Company, General Petroleum Corporation, Union Oil Company of California, T. S. Harrison, and E. H. Watson.

THICKNESS OF SEDIMENTARY ROCKS

Sedimentary rocks that crop out in southeastern Utah range in age from Lower Pennsylvanian to Tertiary (Fig. 1) and some information about the older rocks that intervene between the Lower Pennsylvanian and the pre-Cambrian crystalline rocks is available from drill records and from outcrops in surrounding regions. The following composite

[3] E. M. Spieker, "The Wasatch Plateau Coal Field, Utah," *U. S. Geol. Survey Bull. 819* (1931).

F. R. Clark, "Economic Geology of the Castlegate, Wellington, and Sunnyside Quadrangles, Utah," *U. S. Geol. Survey Bull. 793* (1928).

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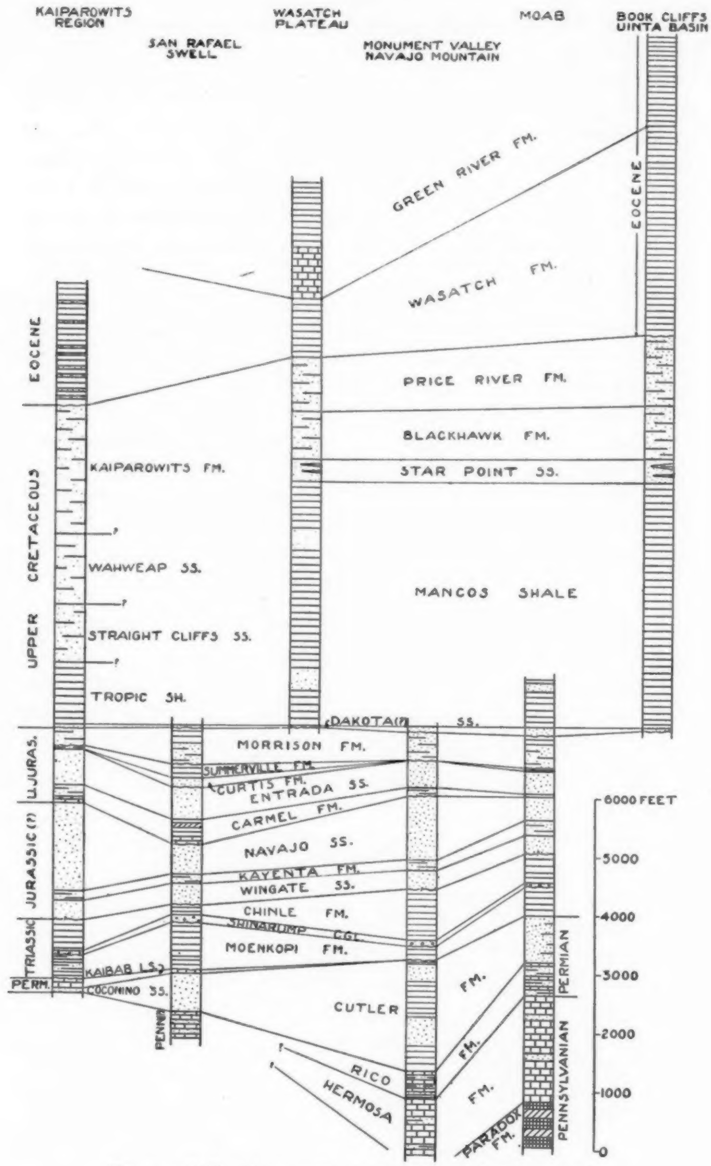


FIG. 1.—Sedimentary rocks exposed in southeastern Utah.

sections in restricted areas supply a fairly definite figure of the thickness of the sedimentary rocks up to the top of the Cretaceous, which was the thickness of the sedimentary series at the time the maximum deformation occurred.

A composite section from the Grand Canyon of the Colorado River in northern Arizona to the Kaiparowits region of Utah[4] includes outcropping rocks ranging in age from the pre-Cambrian to the top of the Cretaceous. The thickness of the pre-Pennsylvanian Paleozoic rocks is slightly more than 1,800 feet, post-Mississippian Paleozoic rocks nearly 2,200 feet, Triassic formations 1,200–1,600 feet, Jurassic (?), and Jurassic formations about 2,500 feet, and the Cretaceous formations about 5,000 feet. The total thickness of pre-Tertiary sedimentary rocks is about 13,000 feet.

A composite section of the sedimentary rocks from the top of the pre-Cambrian crystalline rocks to the base of the Cretaceous in the southeastern corner of Utah has the following thicknesses:[5] limestone which rests on the crystalline rocks as encountered in wells drilled on the Monument upwarp and believed to be entirely of Mississippian age, 1,200–1,700 feet; post-Mississippian Paleozoic rocks, about 3,000–4,000 feet; Triassic formations, about 1,000 feet; Jurassic (?) and Jurassic formations, about 2,000 feet. The total thickness of these pre-Cretaceous formations is about 8,000 feet and if the thickness of about 5,000 feet for the Cretaceous formations in the Kaiparowits region is added, the total thickness of the pre-Tertiary sedimentary rocks may have been about 13,000 feet.

A composite section from the San Rafael Swell to the Book Cliffs does not include the crystalline rocks at the base, but includes all of the Cretaceous.[6] A well which was drilled near the crest of the San Rafael Swell was begun near the top of the Permian and was drilled to a depth of 3,035 feet without encountering crystalline rocks. The

[4] L. F. Noble, "A Section of the Paleozoic Formations of the Grand Canyon at the Bass Trail," *U. S. Geol. Survey Prof. Paper 131* (1923), Pl. 19.
H. E. Gregory, and R. C. Moore, "The Kaiparowits Region," *U. S. Geol. Survey Prof. Paper 164* (1931).

[5] A. A. Baker, "Geology of the Monument Valley-Navajo Mountain Region, Utah," *U. S. Geol. Survey Bull. 865* (in press).
A. A. Baker and J. B. Reeside, Jr., "Correlation of the Permian of Southern Utah, Northern Arizona, Northwestern New Mexico, and Southwestern Colorado," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 11 (November, 1929), pp. 1413–48.
A. A. Baker, C. H. Dane, and J. B. Reeside, Jr., "Correlation of the Jurassic Portions of Utah, Arizona, New Mexico, and Colorado," *U. S. Geol. Survey Prof. Paper 183* (in press).

[6] James Gilluly, "Geology and Oil and Gas Prospects of Part of the San Rafael Swell, Utah," *U. S. Geol. Survey Bull. 806* (1929), p. 129.
F. R. Clark, "Castlegate, Wellington, and Sunnyside Quadrangles, Carbon County Utah," *U. S. Geol. Survey Bull. 793* (1928), Pl. 3.

thichnesses of the overlying Mesozoic formations are: Triassic, 1,000–1,100 feet, Jurassic (?) and Jurassic, about 3,300 feet; Cretaceous, about 7,000 feet. The total known thickness of the pre-Tertiary formations is thus about 14,000 feet, with possibly an additional 2,000–3,000 feet of Paleozoic rocks intervening between the oldest known Paleozoic rocks and the underlying surface of the crystalline rocks.

The Tertiary formations that blanketed southeastern Utah at the end of the Eocene have nearly everywhere been removed by erosion, and in the remaining remnants only partial thicknesses are preserved. An attempt to interpret the former thickness from complete sections exposed at distant localities is likely to lead to erroneous conclusions, because the Eocene sediments apparently were deposited upon a surface of considerable relief, with greater thicknesses deposited in separate basins than were deposited elsewhere. However, the thickness of the Eocene formations that crop out in adjoining regions suggests the order of magnitude of the thickness of the Eocene formations that have been eroded. In the Uinta Basin nearly 7,000 feet of sediments are included in the Eocene.[7] In the western part of the Wasatch Plateau[8] about 4,000 feet of the Eocene formations crop out and the upper part has been removed by erosion. In the vicinity of Bryce Canyon, Utah, near the head of the Paria River, incomplete sections of the Tertiary rocks are 1,300–1,500 feet thick.[9] The Tertiary formations of the Chuska Mountains of northeastern Arizona and northwestern New Mexico have been described by Gregory.[10] The Tohachi shale is 200–1,100 feet thick and the overlying Chuska sandstone is 700–900 feet thick. Gregory tentatively assigned the Tohachi shale to the basal Eocene and suggested the correlation of the Chuska sandstone with the Wasatch formation, so that they probably represent only the Lower Eocene.

CONTOUR MAP

The structure contour map (Fig. 2) shows the attitude of the top of the Upper Triassic Chinle formation in southeastern Utah. The

[7] W. H. Bradley, "Origin and Microfossils of the Oil Shale of the Green River Formation of Colorado and Utah," *U. S. Geol. Survey Prof. Paper 168* (1931), pp. 8–20.

[8] E. M. Spieker, "The Wasatch Plateau Coal Field, Utah," *U. S. Geol. Survey Bull. 819* (1931), p. 16.

[9] H. E. Gregory and R. C. Moore, "The Kaiparowits Region," *U. S. Geol. Survey Prof. Paper 164* (1931), p. 115.

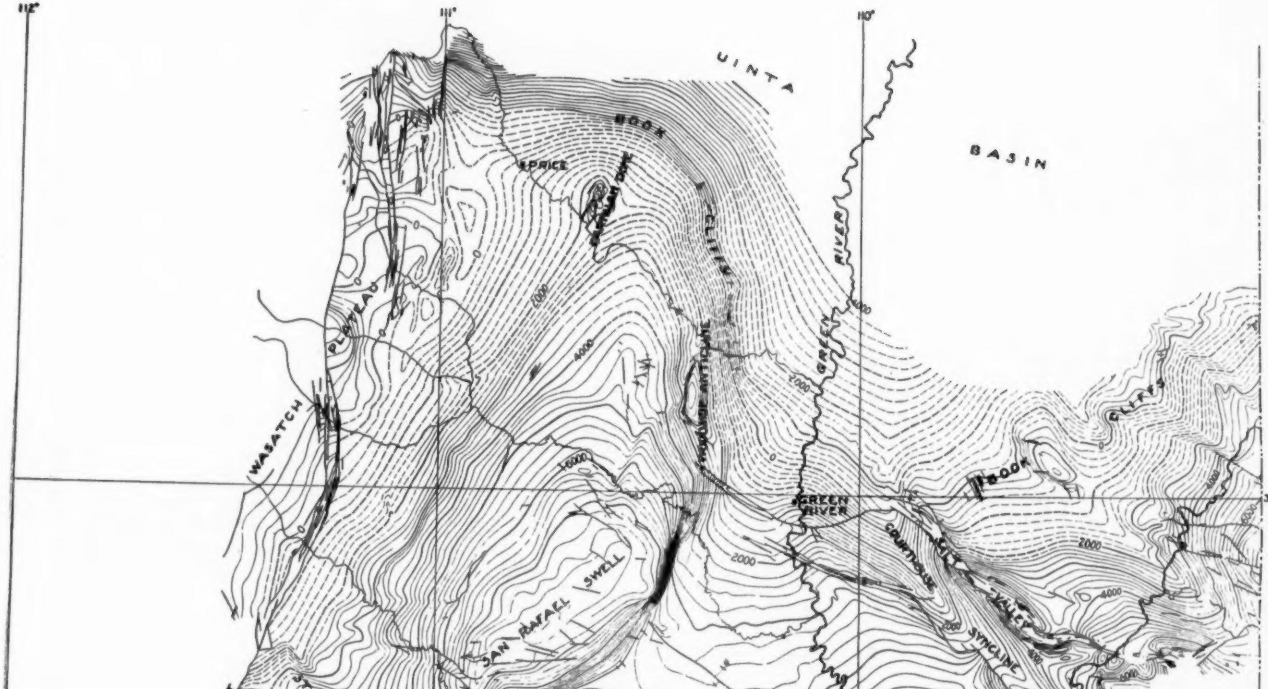
[10] H. E. Gregory, "Geology of the Navajo Country," *U. S. Geol. Survey Prof. Paper 93* (1917), pp. 80–81.

contours are not of the same degree of accuracy in all parts of the map. For a large portion of the area they have been generalized from more detailed structure contour maps; for some of it the structure is known in a general way but controlling elevations are not numerous; and in a small portion contouring is merely diagrammatic. The contours drawn on the surface rocks could not everywhere be transposed to the top of the Chinle formation with confidence. Because of incomplete information concerning the thickness of the formations underlying the Colorado Plateau, and because of the great thickness of sedimentary rocks that occur in some places between the top of the Chinle formation and the surface rocks, no attempt has been made to determine the inclinations of the axial planes of folds, and the position of the axes shown on the contoured horizon is therefore the surface position of the axes of the folds. Similarly, the contours on surface rocks have been raised or lowered vertically through the required stratigraphic interval without regard to whether the folds are of similar or parallel type; along steep monoclines this procedure may introduce considerable error. Throughout the map the consistent practice has been followed of showing the position of the faults as they cut the surface rocks and no attempt has been made to project the fault plane to the top of the Chinle formation, or to indicate whether the faults now extend to that depth or formerly cut that horizon in areas where erosion has cut below it. Obviously, this procedure introduces considerable error in the location of the non-vertical faults, if the horizon contoured is several thousand feet above or below the surface formations, but adequate information to guide the projection of the fault planes is not available and by plotting their location as they cut the surface rocks, their relationships to each other and to the regional structure are preserved unmodified by interpretation.

Essentially, therefore, the structure contour map is a representation everywhere of the surface structure, whether Paleozoic, Mesozoic, or Tertiary rocks are exposed, and is reduced to the horizon of the top of the Chinle formation as a convenient datum to bring the structure contours to numerical conformity. The isolated laccolithic intrusive masses of the Henry, Abajo, and LaSal mountains locally dome the superjacent beds, but are left uncontoured because of the absence of adequate data.

STRUCTURAL FEATURES

The general picture presented by the contour map reveals a few outstanding structural features. The most prominent features of the


112°
111°
110°
39°
UINTA
BASIN
BOOK
CLIFFS
PRICE
GREEN
RIVER
GREEN RIVER
WASATCH
PLATEAU
SAN RAFAEL SWELL
COURTHOUSE
SALT VALLEY
SYNCLINE
MOAB
CANE CREEK ANTICLINE
UPHEAVAL
LA SAL
MTS.
FAULT
THOUSAND
LAKE MT.
STARVATION CREEK ANTICLINE
2000
4000
6000
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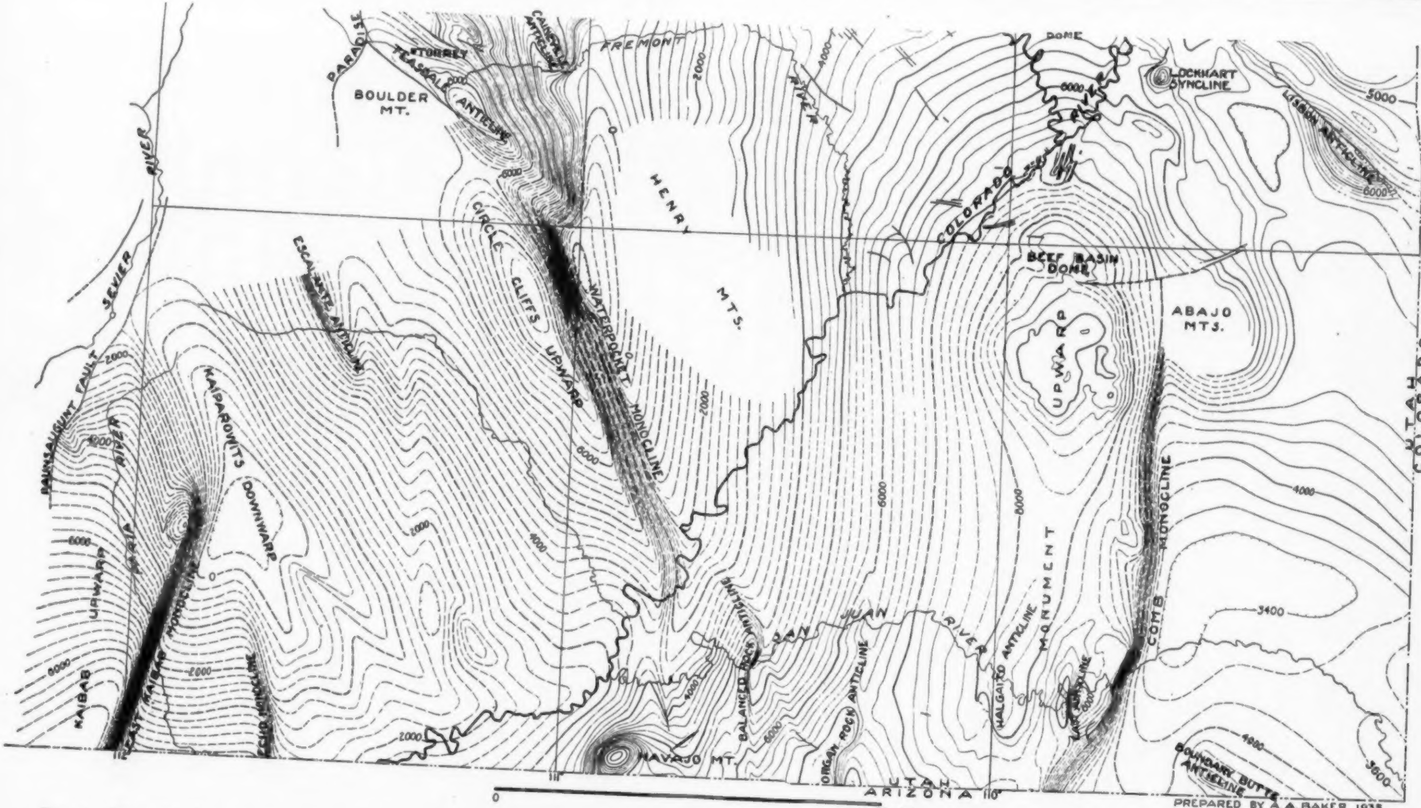

FIG. 2.—Map showing geologic structure of southeastern Utah. Contours drawn at intervals of 200 feet on top of Upper Triassic Chinle formation (sea-level datum).

region are the steep monoclines which form the eastern flanks of large regional upwarps. In the northeastern portion of the mapped area a group of nearly parallel, sharply anticlinal flexures of smaller size, intricately faulted along their crests, forms a distinct structural sub-province in an area underlain by thick salt-bearing deposits. On the northern margin of the area the sweeping curves of the contours outline the southern edge of the Uinta Basin. The nearly symmetrical circular dome of Navajo Mountain in the southern part of the area is believed to exemplify on a smaller scale the areally restricted doming accompanying the laccolithic intrusions in the Henry, LaSal, and Abajo mountains. At the western edge of the area is a zone of faulting that has a north-northeast trend. The east edge of this fault zone forms the structural boundary between the Colorado Plateau and the folded and faulted rocks of the Great Basin at the west.

For convenience of description, the features of the geologic structure of southeastern Utah are grouped into similar types or types of related origin, as follows: (1) large anticlines and synclines with associated small folds, (2) folds and faults in the area underlain by thick salt-bearing deposits, (3) folding related to laccolithic intrusions, and (4) zone of north trending faults and associated folding in the central part of the state.

LARGE ANTICLINES, SYNCLINES, AND ASSOCIATED SMALLER FOLDS

Several large domical uplifts are prominent features of the structural geology of the Colorado Plateau. The San Rafael Swell and the Circle Cliffs, Monument, Kaibab, and Defiance upwarps are of this type. Of these, the San Rafael Swell, Circle Cliffs, most of the Monument, and the northern part of the Kaibab upwarps are in Utah; the Defiance upwarp is in northeastern Arizona. All of these regional uplifts are elongate asymmetrical domes with a short, steep east flank and a long, gently dipping west flank. Minor folds are present on the crests and flanks of the large domes, and those in Utah, with the exception of the San Rafael Swell, have prominent structural troughs on the east.

San Rafael Swell.—The San Rafael Swell is an elongate domical upwarp about 100 miles long and 50 miles wide, extending south from Price. The axis is slightly convex toward the east, but trends about N. 30° E. The crest of the swell is rounded and has several small irregular folds. At a distance ranging from 1 to 5 miles east of the crest, the east flank plunges eastward with a maximum dip of 85° or more; the steepest dips are found approximately opposite the highest part of the dome and the dips gradually flatten toward the

ends of the fold. The zone of steep dips on the east flank ends 6–10 miles east of the axis of the swell, where the rocks in the desert south of Green River are relatively flat. The structural relief of the east flank ranges from 4,000 to 5,000 feet. The west flank, with structural relief of about 8,000 feet, has an average dip of 2° or 3° and extends 30–40 miles to the belt of normal faults at the west edge of the map. At its north end the San Rafael Swell merges with the northward dipping limb of the Uinta Basin, but at the south end it is terminated by the northward dipping monocline forming the northeast flank of the Circle Cliffs upwarp. The Starvation Creek anticline and the Caineville anticline are subsidiary folds on the south end of the swell; they are located on the same structural axis which trends nearly at right angles to the trend of the swell and is closely parallel to the trend of the adjacent steep monocline forming the flank of the Circle Cliffs upwarp. At the north end of the swell the Woodside anticline and the faulted Farnham dome are small folds on the east and west flanks, respectively, of the regional upwarp. Several less prominent subsidiary folds are present on the west flank, especially southwest of Price along the east front of the Wasatch Plateau. Numerous normal faults with the maximum displacement less than 350 feet cut the rocks near the crest of the swell. Most of the faults have a westerly to northwesterly trend, which is approximately transverse to the axial trend. Numerous small faults with similar trend are present in the desert south of the town of Green River lying east of the swell, but none of them is continuous across the belt of steep dips.

Rocks of Permian and Lower Triassic age are the principal surface rocks at the crest of the fold and rocks of Upper Cretaceous, Jurassic, and Cretaceous age crop out on its flanks. All the formations from the Permian to the Cretaceous have an essentially concordant dip.

Circle Cliffs upwarp.—The Circle Cliffs upwarp is an elongate asymmetrical anticlinal fold about 90 miles long and 50 miles wide, whose axis extends from Colorado River near the mouth of San Juan River to Fremont River near Torrey. The upwarp is in two parts; the northern and smaller part, known as the Teasdale anticline, is offset to the northeast and is in échelon with the rest of the fold. A relatively low saddle separates the main part of the upwarp from the Teasdale anticline. The axis of the Teasdale anticline trends about N. 55° W. but the principal axis of the upwarp trends about N. 30° W. The west end of the Teasdale anticline is cut off by a normal fault with downthrow toward the west, which drops flat-lying Tertiary rocks against Jurassic (?) sandstones. The steep monocline forming the northeastern limb of the Circle Cliffs upwarp, known

as the Waterpocket monocline, extends without interruption from Colorado River to Thousand Lake Mountain, where inclined Jurassic (?) sandstones are overlain by the relatively flat-lying Tertiary Wasatch formation. The maximum dip of the monocline is about 75° and the maximum structural relief is more than 8,500 feet in a distance of about 6 miles. The monocline ends at the axis of a syncline which parallels the trend of the monocline and lies 6–12 miles northeast of the axis of the upwarp. The southwestern limb of the Circle Cliffs upwarp near its northern end is concealed under relatively flat-lying rocks of the Wasatch formation; less than 2 miles southwest of the axis of the Teasdale anticline the Wasatch formation rests on the Jurassic (?) Navajo sandstone on the southwest side of a normal fault with downthrow toward the southwest, and the Navajo sandstone is in fault contact with the Moenkopi formation, of Lower Triassic age. South of the limit of these Tertiary rocks which cap Boulder Mountain, the southwest flank of the Circle Cliffs upwarp is about 45 miles wide with a maximum structural relief of nearly 8,000 feet. There are numerous subsidiary anticlines and synclines which modify the long southwest limb of the upwarp, and of the subsidiary folds the Escalante anticline is the most prominent. The northern end of the Escalante anticline is concealed by the Wasatch formation and Tertiary volcanic rocks and south of the limit of Tertiary rocks it plunges southward for about 15 miles to merge with the regional southwesterly dip. The Escalante anticline is an asymmetric fold with a steep west flank and a gently dipping east flank; the rocks on the west flank have a maximum dip of 35° or more and structural relief of about 2,000 feet in a distance of about 1½ miles. It is noteworthy as the most prominent of the few anticlines in southeastern Utah which have west flanks dipping more steeply than their east flanks.

The surface rocks at the crest of the Circle Cliffs upwarp are Permian and Lower Triassic in age and a structurally conformable sequence of progressively younger rocks, including rocks of Upper Cretaceous age, crops out on the flanks of the fold. Relatively flat-lying Tertiary rocks bevel rocks ranging in age from Jurassic (?) to Upper Cretaceous at the north end of the fold.

Monument upwarp.—The Monument upwarp trends nearly south from near the junction of Green and Colorado rivers and extends about 15 miles beyond the Utah State line into northern Arizona. It is about 125 miles long and has a maximum width of about 75 miles. The axis of the upwarp is not everywhere a single well defined axis; at the highest part of the fold, west of the Abajo Mountains,

there are several separate small domes crudely grouped along two more or less parallel axes trending approximately parallel to the general axis of uplift; near the southern end where the upwarp is crossed by the San Juan River it has two well defined axes, one at the crest of the Halgaito anticline and one at the crest of the East (Raplee) anticline, both trending parallel to the regional trend of the uplift. The East anticline, like the Escalante anticline on the Circle Cliffs upwarp, is another conspicuous example of an asymmetric anticline in southeastern Utah, with a steep west flank. There are other subsidiary folds near the crest of the upwarp, including the Beef Basin dome near the north end and the Gypsum Creek anticline in Arizona at the south end. At its north end the upwarp plunges northward and disappears a few miles north of the junction of Green and Colorado rivers. The south end of the Monument upwarp merges with the Tusayan downwarp in northeastern Arizona.[11] Comb monocline, which forms the east flank of the Monument upwarp, is the same type of structural element as the Waterpocket monocline and the monocline forming the east flank of the San Rafael Swell. It is a short steep monocline with a maximum dip of 75°–80° and structural relief of as much as 4,000 feet in 2 miles. At the foot of the monocline the dip flattens abruptly and the monocline is bounded on the east by a broad shallow syncline, except on the west flank of the Abajo Mountains, where the arching of the sedimentary rocks over the laccolithic intrusive rocks of the mountains causes an abrupt rise toward the east from the foot of the monocline. Toward the south in Arizona the monocline swings in a great arc convex toward the south and with gradually decreasing dip and merges with the regional dip near Kayenta, Arizona, about 15 miles south of the State line. The long west flank of the Monument upwarp extends to the synclinal axis at the foot of the Waterpocket monocline and has a maximum structural relief of more than 10,000 feet. It has a fairly regular westerly dip of a few degrees except where the strata are arched over the laccoliths of the Henry Mountains, and in a belt of country lying mostly south of San Juan River, where subsidiary folding has occurred. West of the Halgaito anticline in the country south of San Juan River the rocks are arched in the Organ Rock anticline and the Balanced Rock anticline. Both of these folds are similar to the large regional upwarps, in that they have a northerly trend and are asymmetric, with gently dipping west limbs and steeply dipping east limbs. The east limb of the Organ Rock anticline rises

[11] H. E. Gregory, "Geology of the Navajo Country," *U. S. Geol. Survey Prof. Paper 93* (1917), p. 112.

about 1,000 feet in 1 mile near the State line and the east limb of the Balanced Rock anticline rises about 1,000 feet in ½ mile near San Juan River. Both of these anticlines die out a few miles north of the river.

A few small normal faults are present on the Monument upwarp and trend more or less at right angles to the strike of the rocks.

The oldest rocks exposed on the upwarp are of Pennsylvanian age and they crop out only in the canyons of the San Juan and Colorado rivers. Rocks of Permian and Triassic age crop out extensively on the crest of the fold and progressively younger rocks with concordant dip up to and including the Upper Cretaceous crop out on the flanks.

Kaibab upwarp.—The Kaibab upwarp is a large asymmetrical upwarp about 150 miles long, extending from south of the Grand Canyon, Arizona, into southern Utah; only the northern third is in Utah. The axis of the upwarp forms a great arc convex toward the west, trending about N. 15° W. near its southern end and about N. 15° E. at its northern end. From a high point on the Kaibab Plateau a few miles north of the Grand Canyon, Arizona, the crest of the upwarp plunges northward and southward. The upwarp has relatively low relief at its north end, where it is cut off by the Paunsaugunt fault; folding in the older rocks northwest of the fault is concealed by downfaulted, relatively flat-lying Wasatch and Tertiary volcanic rocks. The plunging south end of the upwarp flattens and loses its identity about 30 miles south of the Grand Canyon.[12] There is a small subsidiary fold (Butler Valley dome) near the crest at the northern end of the Kaibab upwarp. The east limb of the upwarp is the steep limb of the asymmetric fold and is known as the East Kaibab monocline. Plunging abruptly from near the axis of the upwarp, the monocline dips eastward with a maximum dip of about 65°. At the foot of the monocline the dip also changes abruptly to the nearly flat-lying beds of the Kaiparowits downwarp in the northern part, and farther south to the gently northward dipping structural platform which extends to the top of the Echo monocline. The steeply dipping east limb of the upwarp is 2–3 miles wide and has a structural relief along the steeper part of the monocline ranging from 3,000 to more than 5,000 feet. Incomplete information is available concerning the west limb of the upwarp. At its northern end it is cut off by the Paunsaugunt fault, less than 20 miles west of the crest, but farther south it extends with a gentle dip 30–50 miles to the Sevier fault, which is west of the boundary of the map, and still farther south in

[12] N. H. Darton, "A Resumé of Arizona Geology," *Univ. of Arizona Bull. 119* (1925), Pl. 52.

the vicinity of the Grand Canyon it is terminated by a shallow syncline whose axis lies about 35 miles southwest of the axis of the upwarp.[13] The Paunsaugunt and Sevier faults are elements of the fault system trending northward through central Utah that forms the western limit of the Colorado Plateau structural province of southeastern Utah. The Paunsaugunt and Sevier faults are of Tertiary age and the downthrow of several hundred to several thousand feet is toward the west.

The surface rocks at the crest of much of the Kaibab upwarp are of Permian age, but older Paleozoic rocks crop out in some canyons, and rocks of pre-Cambrian age crop out in the Grand Canyon. A structurally conformable series of post-Permian rocks ranging in age up to and including the Upper Cretaceous crops out on the flanks of the upwarp, and relatively flat-lying rocks of Tertiary age overlie the Cretaceous rocks with angular discordance.

Echo monocline.—The Echo monocline is an eastward dipping monocline that passes through Lee's Ferry, Arizona, and is more or less parallel to and 15–20 miles east of the East Kaibab monocline. The monocline is about 90 miles long, but extends only about 20 miles north of the Arizona-Utah State line. The portion of the monocline in Utah has a maximum dip of about 30° and a maximum structural relief of about 1,500 feet. The belt of steep dips is less than 2 miles wide and at both the top and base of the monocline the dip changes abruptly to a gentle north dip. Surface rocks of Triassic to Upper Cretaceous age are involved in the folding.

Folding in southeastern corner of Utah.—Between the Comb monocline on the east side of the Monument upwarp and the Utah-Colorado State line lies a strip of the state 30 miles or more in width in which the surface rocks are, for the most part, in the Morrison and Dakota (?) formations. The surface rocks are steeply upturned around the Abajo Mountains and are arched in a sharp fold to form the Boundary Butte anticline at the Utah-Arizona State line, but elsewhere they have a very gentle dip on broad low anticlines and shallow synclines. The geologic structure of the Abajo Mountains is discussed elsewhere in this paper in connection with the discussion of the laccolithic mountains of southeastern Utah. The axis of the Boundary Butte anticline trends about N. 65° W., but at the northwest end of the anticline the axis swings nearly due north. The west and southwest flank of the part of the fold in Utah has a maximum dip of 12° or more, but the belt of steep dips does not exceed a mile in width, as there is a rapid change in dip toward the syncline which

[13] N. H. Darton, *op. cit.*

separates the Boundary Butte anticline from the Comb monocline. The northeast flank of the anticline dips gently toward the axis of a shallow syncline that follows approximately the course of San Juan River near the southeast corner of the State. The Navajo sandstone and possibly the underlying Kayenta formation are the surface rocks at the crest of the Boundary Butte anticline. The syncline separating the Boundary Butte anticline from the Comb monocline deepens toward the northeast and merges with a large shallow structural basin whose axis is about 8 miles north of San Juan River and trends N. 80° W. North of the axis of the shallow structural basin the rocks rise northeastward 1,600 feet in about 30 miles, to the crest of a very low dome, east of the Abajo Mountains; the Dakota (?) sandstone forms a dip slope along most of this belt of southwestward dipping rocks. A shallow syncline about 4 miles northeast of the axis of the dome separates it from the southwest limb of the Lisbon anticline.

Uinta Basin.—The Uinta Basin is a regional downwarp occupying a large part of northeastern Utah. Its approximate boundaries are the Book Cliffs on the south, the Utah-Colorado State line on the east, the Uinta Mountains on the north, and the Wasatch Range on the west. The basin is about 125 miles wide east and west, and about 110 miles wide north and south, but only the sinuous southern edge is shown on the map (Fig. 2). It extends westward from Colorado River at the Utah-Colorado State line in a great arc convex toward the south. In the vicinity of Green River the trend of the basinward dipping rocks swings northward along the east flank of the San Rafael Swell; the trend continues northward for about 40 miles and then swings due west to the limits of the map a few miles northwest of Price. The maximum dip of the basinward dipping rocks is about 12°, although the average dip is less than 8°. A number of minor folds modify the regional monoclinal dip, particularly near the Utah-Colorado State line. Most of these minor folds have a northwest trend and the limbs of the folds dip more or less at right angles to the regional monoclinal dip.

Rocks of Upper Cretaceous age crop out in the Book Cliffs escarpment along the southern rim of the Uinta Basin, but a few miles back of the rim the Cretaceous rocks are unconformably overlain by the Wasatch formation of Eocene age. The center of the basin is underlain by the Green River formation and other younger Tertiary formations.[14]

[14] W. H. Bradley, "Origin and Microfossils of the Oil Shale of the Green River Formation of Colorado and Utah," *U. S. Geol. Survey Prof. Paper 168* (1931), pp. 9–22.

FOLDS AND FAULTS IN AREA UNDERLAIN BY THICK SALT-BEARING BEDS

Parts of southeastern Utah and southwestern Colorado are underlain by the Paradox formation, a thick series of salt-bearing beds of early Pennsylvanian age. Although the rocks included in this formation crop out at numerous localities and have been recorded in the literature since 1875,[15] all of the outcrops are isolated and are accompanied by faulting and steep tilting of adjacent strata, so that stratigraphic relations are obscure. It was not until many wells had been drilled in exploration for oil and gas and until much of the region had been covered by detailed geologic work, that it became apparent that a thick series of salt-bearing beds underlies a large area and that the outlines of the basin of deposition could be drawn.[16] The basin has an oval shape, with its long axis extending 150 miles or more southeastward from the vicinity of the town of Green River, Utah, into Colorado near the southwest corner of the state; the short axis is approximately 80 miles long and extends from near the mouth of the Fremont River in Utah to the west side of the Uncompahgre Plateau in western Colorado (Fig. 3).

Within the limits of the basin as thus outlined the structure of the surface rocks has many features that are not found elsewhere in Utah. Superimposed upon the larger structural features, such as the Uinta Basin on the north, and the Monument upwarp on the southwest, is a system of faults and folds with a northwest trend and numerous small folds and faults with different trends.

The most striking structural features in this part of Utah are the northwestward trending Lisbon, Moab-Spanish Valley, and Salt Valley faulted folds. The Moab-Spanish Valley and the Salt Valley faulted folds are offset successively toward the northeast from the Lisbon faulted fold in *en échelon* arrangement. However, a zone of faulting continues northwestward from the end of the Moab-Spanish Valley fold more or less parallel to the Salt Valley anticline. At the southeastern end of Salt Valley the trend of the faulted belt swings eastward and continues with some interruption nearly to the Utah-Colorado State line.

The Lisbon faulted fold trends about N. 50° W. and is about 20 miles long. It is an elongate uplift rising abruptly from the nearly flat lying beds on the southwest; its southwest flank has a maximum

[15] A. C. Peale, "Geological Report on the Grand River District," *U. S. Geol. and Geog. Survey Terr. Ninth Ann. Rept.* (1875), pp. 71–77.

[16] A. A. Baker, C. H. Dane, and J. B. Reeside, Jr., "Paradox Formation of Eastern Utah and Western Colorado," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 8 (August, 1933), pp. 963–80.

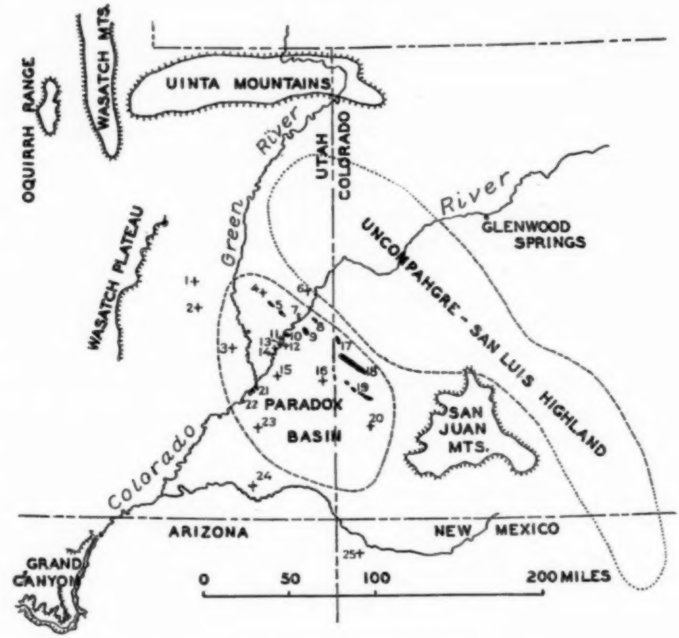

FIG. 3.—Map showing inferred limits of Paradox basin.

EXPLANATION OF LOCALITY NUMBERS

1. Black Box Canyon of San Rafael River
2. Straight Wash
3. Phillips Petroleum Company's well
4. Crescent Eagle Oil Company's well
5. Outcrops of Paradox formation in Salt Valley
6. Utah Southern Oil Company's State well No. 1
7. Outcrops of Paradox formation in Cache Valley
8. Outcrops of Paradox formation in Onion Creek
9. Outcrops of Paradox formation in valley of Castle Creek
10. Outcrops of Paradox formation in Moab Valley
11. Midwest Refining Company's J. L. Shafer well No. 1-A
12. Snowden and McSweeney's Prommel well No. 1
13. Midwest Refining Company's Frank Shafer well No. 1
14. Midwest Refining Company's J. H. Shafer well No. 1
15. Empire Gas and Fuel Company's well
16. Union Oil Company's well in Lisbon Valley
17. Outcrops of Paradox formation in Sinbad Valley
18. Outcrops of Paradox formation in Paradox Valley
19. Outcrops of Paradox formation in Gypsum Valley
20. Transcontinental and Ohio Oil Company's well
21. Outcrops of Paradox formation in Canyon of Colorado River
22. Outcrop of Paradox formation in Gypsum Canyon
23. Midwest Refining Company's Elk Ridge well
24. Utah Southern Oil Company's Cedar Mesa well
25. Continental Oil Company's wells in the Rattlesnake field

structural relief of about 4,000 feet in a distance of about 6 miles. A normal fault with downthrow toward the northeast and displacement of more than 3,000 feet follows, approximately, the crest of the anticline. Northeast of the fault the northeast flank of the anticline extends about 3 miles to the axis of an adjoining syncline and has structural relief of about 1,500 feet. The axial fault extends several miles beyond the ends of the fold. The surface rocks at the crest of the fold are in the Hermosa formation, of Pennsylvanian age, but northeast of the axial fault the surface rocks are in the Morrison formation, of Upper Jurassic age. The Paradox formation does not crop out on the Lisbon anticline, but was encountered at a depth of about 1,600 feet in a well drilled near the crest of the fold by the Union Oil Company of California.

The long valley extending about S. 45° E. from Colorado River at Moab includes Moab and Spanish valleys. Along both sides of the valley are belts of normal faults and the downthrow of most of them is toward the valley; the fault zones are made up of a number of short faults, all having approximately the same trend. The maximum throw of an individual fault is 500 feet and the displacements of the others are 300 feet or less. At many places, especially on the southwest side of the valley, the strata in the fault zones and on the valleyward side of the fault zones have a dip as high as 30° or 40° toward the valley. At Moab, near the northwest end of the valley, the general structure is that of an anticline with faulted flanks; the southwest flank of the anticline is cut by several normal faults which have an aggregate downthrow toward the valley of several hundred feet, but on the northeast flank the faults are small and do not all have downthrow in the same direction, so that the net aggregate displacement is not large. Five or six miles southeast of Moab the structure of Spanish Valley is a faulted syncline with a gently dipping slightly faulted northeast limb and a steeply dipping southwest limb which is cut by several normal faults. Near the southeast end of the valley, where it is terminated by the LaSal Mountains, the structure is that of a graben cutting more or less uniformly southward dipping rocks. Zones of small normal faults limit the graben. Within it the rocks are folded into a syncline with steeply dipping limbs that are terminated at the fault zones. Gypsiferous beds of the Paradox formation crop out in Moab Valley, where they have been intruded into overlying formations and are in contact with rocks as young as the Chinle formation, of Upper Triassic age. Elsewhere the surface rocks in the floor and walls of the valley range in age from Pennsylvanian to Upper Cretaceous.

The fault zone on the northeast side of Moab Valley terminates near Colorado River, but the fault zone on the southwest side continues northwestward 45 miles or more. For a distance of about 10 miles northwest of Colorado River this fault zone has the same trend as the valley and consists of a single fault with a maximum downthrow toward the northeast of about 2,600 feet, but farther northwest the trend of the fault zone swings to about N. 70° W. and it consists of numerous small faults which in part limit down-dropped blocks or grabens. At the locality of maximum displacement there is a sharp domical uplift southwest of the fault with structural relief on the southwest flank of 1,400 feet in about two miles; the fault follows the crest of the fold and cuts off the northeast flank. The character of this fold is similar to that of the Lisbon anticline.

The Salt Valley faulted fold is in part similar to the Moab-Spanish Valley faulted fold. The Salt Valley fold is an anticline trending about N. 50° W. Parallel more or less continuous fault zones follow each limb of the fold near the crest. The fault zones consist in most places of a great number of sub-parallel short faults in part trending at an angle with the anticlinal axis, and locally the zones merge to form one broad belt of faulting occupying the whole crest of the fold. It is possible that faulting at the crest of the anticline between the limiting fault zones is more prevalent than indicated on the map, as the center of the valley is largely covered by alluvium and faults, if present, could not be observed. The southwest flank of the anticline has a structural relief of about 2,500 feet in a distance of about 4 miles between the fault zone at the crest and the axis of the Courthouse syncline, which is approximately parallel to the Salt Valley anticline and adjoins it on the southwest. The dip of the northeast flank of the anticline is in general less steep than the dip on the southwest flank, but dips at the rate of 1,000–2,500 feet in 3 miles. At the southeast end of Salt Valley the trend of the zone of faulting and folding swings nearly due east and is more or less continuous nearly to the Utah-Colorado State line. East of the end of Salt Valley the disturbed belt is not a relatively simple faulted anticline, but consists of several small sharply folded domes and basins which are cut by numerous faults that are parallel to the general trend of the belt, but do not form continuous fault zones. At the northwest end of Salt Valley a series of small faults forms a zone of faulting that extends for a distance of 25 miles, with a westerly trend more or less parallel with, and 4 miles or more north of, the zone of faulting that forms a continuation of the Moab-Spanish Valley faulted fold.

The Paradox formation crops out at several places in Salt Valley and in the part of the fault zone lying east of Colorado River. The plastic salt-bearing beds of the Paradox formation have been intruded into the overlying formations in the form of plugs or elongate masses and are in contact with beds as young as Upper Triassic.

Elsewhere in southeastern Utah the Paradox formation crops out only in Castle Creek Valley about 12 miles northeast of Moab and in the canyon of Colorado River below its junction with Green River. Castle Creek Valley follows the crest of an anticline which trends about N. 55° W. and plunges northwestward on the north flank of the LaSal Mountains. A plug of igneous rock crops out in the southeast end of the valley. The Paradox formation crops out, though poorly exposed, in an aureole surrounding the plug of igneous rock and also in a narrow strip along the edge of the alluvium on the southwest side of the valley. Along Colorado River below the mouth of Green River three small domelike masses of gypsum crop out in the bottom of the canyon, and a fourth outcrop is reported in a side canyon.[17] At these outcrops the relatively plastic rocks of the Paradox formation have been forced upward, causing an arching and rupturing of the overlying Hermosa formation. In the vicinity of the junction of the Green and Colorado rivers and for several miles upstream and downstream along Colorado River the rocks in the lower canyon walls dip away from the rivers with dips of as much as 30°. This fold that follows the bed of the canyon is known as the Meander anticline; it clearly indicates an upward thrust from the underlying mass of plastic salt-bearing beds where the strength of the overlying rocks had been weakened by the cutting of the canyon. The arching of the rocks in the Meander anticline is not shown on the structure contour map. On both sides of Colorado River just below the mouth of Green River the rocks on the plateau near the canyon rim are broken by several faults, with a maximum displacement of a few hundred feet. The faults are more or less parallel with the river and with each other and bound grabens which have an average width of about 500 feet. The grabens on the east side of the river are located in a shallow syncline. On that side of the river it is also clearly evident that the grabens have formed very recently in geologic time, as numerous former drainage channels have been interrupted by the downdropped block in the graben. The relation of the structural features to the canyon and the evidence of recent faulting clearly indicate that these features are related to recent plastic flowage of the salt-bearing rocks

[17] Sidney Paige, oral communication.

and to movement of this material from areas adjoining the river into domes and arches along the river.

There are several small domical folds and structural depressions along Colorado River or within a few miles of the river between Moab and the mouth of Green River. The majority of them trend about N. 50° W., in conformity with the dominant trend of faults and folds in this part of the state, but some of them have a more westerly trend and some are roughly circular in outline. Two of the folds may be mentioned specifically, as they are of somewhat unusual types.

The Lockhart syncline, which centers in the upper part of Lockhart Canyon, about 5 miles east of the river, is a small, roughly circular structural basin. The closed part of the basin is approximately 2½ miles in diameter and more than 700 feet deep. The Upheaval dome is located about 18 miles north of the junction of Green and Colorado rivers and about 10 miles west of Colorado River. It consists of a ringlike syncline surrounding a central dome. The composite structure is circular in shape and approximately 3 miles in diameter. The axis of the ringlike syncline is depressed about 400 feet and the peak of the central dome rises about 1,700 feet above the axis of the syncline. The rocks in the area surrounding this structural feature are essentially horizontal.

In the region between Green and Fremont rivers are numerous small normal faults, most of which trend about N. 50° W. The displacement on most of the faults is 100 feet or less and the downthrown side is toward the southwest on some of the faults and toward the northeast on others. Where the faults are closely spaced they commonly limit horsts or grabens.

FOLDS RELATED TO LACCOLITHIC INTRUSIONS

A laccolith (laccolite), as defined by Gilbert[18] in his report on the Henry Mountains, is a body of igneous rock that has "insinuated itself between two strata, and opened for itself a chamber by lifting all the superior beds." It is clear from this definition that the arching of strata due to the intrusion of laccoliths is confined to the strata overlying the laccolith and that the strata underlying the laccolith are practically undisturbed.

The Henry Mountains, the type locality of laccoliths, are located in southeastern Utah. The neighboring LaSal and Abajo mountains are also of laccolithic origin. Navajo Mountain dome, located near the Utah-Arizona State line, south of the mouth of San Juan River,

[18] G. K. Gilbert, "Geology of the Henry Mountains," *U. S. Geog. and Geol. Survey of the Rocky Mountain Region* (1877), p. 19.

is a nearly symmetrical circular dome with a diameter of 7 or 8 miles and structural relief of about 2,000 feet. Although there are no exposures of igneous rock in Navajo Mountain, there is little doubt that it represents the intrusion of a single laccolith. The other mountains are composed of more than one laccolith and the composite arching over the several laccoliths produces a complicated system of folding. However, no structure contour maps depicting the folding in the Henry, LaSal, or Abajo mountains are available and the areas covered by the mountains are blank on the map (Fig. 2). At the foot of the laccolithic mountains the strata dip 30° or more, but the dip flattens abruptly outward and merges with the regional dip of the rocks.

ZONE OF NORTH-TRENDING FAULTS AND ASSOCIATED FOLDS IN CENTRAL PART OF STATE

At the western edge of the map (Fig. 2) is a zone of faulting tha has a north-northeast trend through the central part of Utah. The east edge of this fault zone forms the boundary between the relatively flat-lying unfaulted rocks of the Colorado Plateau and the folded and faulted rocks of the Great Basin on the west. Incomplete information is available concerning faulting in this zone and the faults are not all shown on the map; also some of the faults are not shown throughout their full extent. The faults have more or less of an échelon arrangement, with the faults toward the north lying farther east. All of the faults are of the normal type and are vertical or nearly vertical. Toward the south the fault zone consists of single faults with displacements which locally exceed 1,500 feet, down toward the west. Farther north the fault zone is more complex and consists of numerous faults with more or less parallel trends.[19] The downthrown sides of the faults are not all in the same direction and in general the zone is a series of grabens, although there is much subsidiary faulting within some of the downdropped blocks. The displacements along the graben faults are as much as 2,500 feet. Tertiary formations are involved in the faulting and in many places where older rocks are faulted against Tertiary volcanics it is impossible to determine the amount of the displacement.

Along the southern part of the fault zone the regional structure of the Plateau Province abuts against the faults with very little modification. Toward the north, however, the rocks are folded into many small, more or less faulted anticlines, synclines, and monoclines

[19] E. M. Spieker, "The Wasatch Plateau Coal Field, Utah," *U. S. Geol. Survey Bull. 819* (1931), pp. 53–58.

in areas adjacent to and within the fault zone. The regional northwest dip of the northwest flank of the San Rafael Swell merges with this belt of folding and is not clearly defined in the Wasatch Plateau.

PERIODS OF DEFORMATION

Folding and regional warping have occurred many times during the geologic history of southeastern Utah. The most important known periods of crustal movement occurred during the early Pennsylvanian, near the close of the Cretaceous, and during one or more periods in the Tertiary. Little is known of the structural deformation prior to the Carboniferous because of the lack of information concerning rocks of early Paleozoic age in the Plateau region.

Although rocks of Mississippian age do not crop out in the Plateau region, rocks equivalent to the Madison limestone, of early Mississippian age, crop out in northern Arizona,[20] western Colorado,[21] and northern and western Utah,[22] and it is assumed that they were deposited across the intervening plateau region of southeastern Utah. The presence of Mississippian limestone beneath Salt Valley is suggested by the presence there of outcrops of a conglomerate with large boulders of limestone and chert which contain fossils of probable Mississippian age, and Mississippian limestone is believed to be present elsewhere in southeastern Utah where wells have been drilled into a thick series of limestone that apparently is older than the Pennsylvanian Hermosa formation. The available evidence does not clearly indicate what part of the Mississippian is represented by this limestone, but possibly it is equivalent to the Madison limestone, as post-Madison Mississippian rocks are present in the surrounding region only in northwestern Utah. The earliest Pennsylvanian of southwestern Colorado, the Molas formation, with which the conglomerate that crops out in Salt Valley is tentatively correlated, reflects by its conglomeratic character the occurrence of a period of erosion during which fossiliferous Lower Mississippian chert boulders were formed and incorporated in the earliest Pennsylvanian sediments. It therefore seems probable that southeastern Utah was above sea-level and exposed to erosion during the later Mississippian.

[20] N. H. Darton, "A Résumé of Arizona Geology," *The University of Arizona Bull. 119* (1925), p. 64.

[21] Edwin Kirk, "The Devonian of Colorado," *Amer. Jour. Science*, 5th ser. Vol. 22 (1931), pp. 220–40.

[22] B. S. Butler, "The Ore Deposits of Utah," *U. S. Geol. Survey Prof. Paper 111* (1920).

James Gilluly, "Geology and Ore Deposits of the Stockton and Fairfield Quadrangles, Utah," *U. S. Geol. Survey Prof. Paper 173* (1932), pp. 22–25.

The first important folding in the decipherable history of the region either accompanied the elevation of the land above sea-level or occurred shortly afterward, near the close of the Mississippian or early in the Pennsylvanian. The elevation of the ancient land mass in western Colorado variously known as the San Luis Mountains, Uncompahgre-Sangre de Cristo element, and Uncompahgre-San Luis highland, began during this period of deformation. The lithology, thickness, and distribution of the Pennsylvanian and Permian sediments adjacent to this highland shows that the deformation was in progress during the early Pennsylvanian and continued at least to the close of the Carboniferous.[23] West of the highland, in what is now the Colorado Plateau province, the salt-bearing sediments of the lower Pennsylvanian Paradox formation accumulated in a structural trough adjacent to the highland[24] and were succeeded by the Hermosa formation, also of Pennsylvanian age, which, near the old highland, consists of coarse conglomerates and other clastics interbedded with marine limestones, the assemblage suggesting rapid deposition in a subsiding trough. The Hermosa wedges out westward by overlap upon the Mississippian sediments, which had been arched in a broad, low anticline the crest of which apparently was located near the Grand Canyon, Arizona, where locally all rocks of Pennsylvanian age are absent and the Permian Supai formation rests upon the Redwall limestone, of Mississippian age.[25]

Near Fort Defiance, in eastern Arizona, Permian Red-beds rest on pre-Cambrian crystalline rocks.[26] This relationship indicates that an uplift may have occurred at this locality during the early Pennsylvanian deformation and that it was of such size and elevation that it was not submerged by the Pennsylvanian sea; the erosion of this land area stripped the cover of sedimentary rocks from the crystalline rocks, and it was not until the Permian that the crystalline rocks were again covered by sediments. Although it seems probable that

[23] F. A. Melton, "The Ancestral Rocky Mountains of Colorado and New Mexico," *Jour. Geol.*, Vol. 33, No. 1 (1925), pp. 84–89.
C. H. Dane, "Uncompahgre Plateau and Related Structural Features" (abstract), *Jour. Wash. Acad. Sci.*, Vol. 21 (1931), p. 28.

[24] A. A. Baker, C. H. Dane, and J. B. Reeside, Jr., "The Paradox of Eastern Utah and Western Colorado," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 8 (August, 1933), pp. 976–79.

[25] David White, "Flora of the Hermit Shale, Grand Canyon, Arizona," *Carnegie Inst. Washington Pub. 405* (1929), p. 11.

[26] H. E. Gregory, "Geology of the Navajo Country," *U. S. Geol. Survey Prof. Paper 93* (1917), pp. 17, 27.
A. A. Baker and J. B. Reeside, Jr., "Correlation of the Permian of Southern Utah, Northern Arizona, Northwestern New Mexico, and Southwestern Colorado," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 11 (November, 1929), p. 1427.

this uplift near Fort Defiance occurred during the early Pennsylvanian deformation, it is possible that it occurred during some earlier period of deformation and that a land area was present at this locality during Mississippian time.

During the deposition of most of the Pennsylvanian and Permian sediments, southeastern Utah was a relatively stable region. There was some oscillation of the land with respect to sea-level, as both marine and continental sediments were deposited during the Permian.

Near the close of the Permian some low folds were formed near Moab,[27] as shown by angular discordance between the Permian Cutler formation and the overlying Lower Triassic Moenkopi formation and by thinning of the Cutler formation at the crests of anticlines. Angular discordance between the Lower Triassic Moenkopi formation and the Permian Cutler formation on the southwest flank of the Uncompahgre Plateau shows that uplift of the ancient land mass in western Colorado was still in progress at the end of the Permian.[28] An erosional unconformity with slight relief has been recognized at the top of the Permian at many localities in the Plateau region and the Plateau region as a whole was marked, therefore, by only a slight almost uniform elevation of the land with respect to sea-level, followed by a widespread lowering of the land and partial submergence by the Lower Triassic Moenkopi sea.

In the interval between the deposition of the Lower Triassic Moenkopi formation and the Upper (?) Triassic Shinarump conglomerate, slight folding occurred in southeastern Utah and there was further elevation of the Uncompahgre-San Luis highland. Angular discordance between the Moenkopi and the overlying formations near Moab, and thinning of the Moenkopi at the crest of the Cane Creek anticline prove the occurrence of slight folding which apparently resulted in further growth of the same folds that were formed at the close of the Permian.[29] Through most of southeastern Utah no angular discordance has been observed at the top of the Moenkopi, but Gregory and Moore[30] observed slight discordance at several localities in the Circle Cliffs. The Moenkopi formation wedges out beneath an angular unconformity on the southwest flank of the

[27] A. A. Baker, "Geology and Oil Possibilities of the Moab District, Grand and San Juan Counties, Utah," *U. S. Geol. Survey Bull. 841* (1933), p. 77.

[28] C. H. Dane, "Geology of the Salt Valley Anticline and Adjacent Areas, Grand County, Utah," *U. S. Geol. Survey Bull. 863* (in press).

[29] A. A. Baker, *op. cit.* p. 77.

[30] H. E. Gregory and R. C. Moore, "The Kaiparowits Region," *U. S. Geol. Survey Prof. Paper 164* (1931), p. 52.

Uncompahgre Plateau,[31] showing that there was further uplift and erosion of the plateau before the Chinle formation was deposited.

A long period in which continental conditions prevailed followed the deposition of the Moenkopi formation. During this period there seems to have been nearly continuous deposition of 1,500–2,500 feet of sediments included in the Upper (?) Triassic Shinarump conglomerate, Upper Triassic Chinle formation, and Jurassic (?) Wingate sandstone, Kayenta formation, and Navajo sandstone. Southeastern Utah was a relatively stable region and the highland in western Colorado, which had been rising more or less intermittently since the late Mississippian or early Pennsylvanian and had been a source of sediments since that time, also remained relatively stable; the highland was buried by the Chinle formation during the Upper Triassic. Continental conditions were terminated at the end of Navajo time by the incursion of the southward advancing Upper Jurassic sea in which the Carmel formation was deposited. Because a thickness of 1,500–2,500 feet of continental sediments had been deposited across the region between the invasions of the Moenkopi and Carmel seas, there was a regional subsidence of that amount, either coincident with the deposition of the sediments or at the close of Navajo time, so that the land surface was at or near sea-level at the beginning of Carmel time. This subsidence may have been accompanied by a gentle westward tilting of the region, because a greater thickness of continental sediments and of the Carmel formation was deposited in southwestern Utah than in the eastern part of the State; the tilting may have resulted in slight uplift in western Colorado.

The partial withdrawal of the Carmel sea was followed apparently without lapse of time by the deposition of the continental and possibly in part marine sands of the Entrada sandstone. The land was again submerged by another advance of the Upper Jurassic sea in which the Curtis and possibly the Summerville formations were deposited. The overlying Morrison formation, deposited under continental conditions, is the uppermost Jurassic formation in the region. The alternating marine and continental sediments of the Upper Jurassic indicate that the land surface oscillated with respect to sea-level. Angular discordance has been observed at the top of the Entrada sandstone[32] and at the top of the Summerville formation,[33] but it has

[31] C. H. Dane, *op. cit.*

[32] James Gilluly, "Geology and Oil and Gas Prospects of Part of the San Rafael Swell, Utah," *U. S. Geol. Survey Bull. 806* (1929), p. 105.

[33] James Gilluly, *op. cit.*, p. 111.
A. A. Baker, "Geology of the Green River Desert and the East Flank of the San

been observed only in local areas and outcrops elsewhere in the region do not indicate that important folding occurred during the Upper Jurassic.

Southeastern Utah was a land area during the Lower Cretaceous and received practically no sediments, but the region was submerged by the westward advancing Mancos sea in the Upper Cretaceous. The strand line of the Mancos sea was constantly shifting and continental coal-bearing sediments were deposited in the west contemporaneously with marine shale in the east. The net result of successive advances and recessions of the sea was an eastward migration of the strand line until the continental sediments covered southeastern Utah. A period of erosion began near the Wasatch Plateau as terrestrial deposits of the Price River formation accumulated in basins on the east.[34]

The most important period of crustal deformation in the legible structural history of southeastern Utah occurred at or near the end of the Cretaceous, contemporaneous with the great mountain-building movements in the Rocky Mountains. The huge regional folds such as the San Rafael Swell, Circle Cliffs, Kaibab, and Monument upwarps, and probably most of the smaller folds shown on the map, were formed during this period of folding. Although rocks of Tertiary age have been removed by erosion from most of the region, the relation of the remnants of Tertiary rocks to the underlying formations clearly indicates the date of the deformation. Throughout the region, except in the Uinta Basin, the Upper Cretaceous formations, where present, are involved in the folding, but the Eocene Wasatch formation rests on an eroded surface of the folded older formations, bevelling rocks as old as Jurassic. Spieker and Reeside[35] mention an angular discordance at the base of the Wasatch formation in the Wasatch Plateau; at Thousand Lake and Boulder mountains, rocks assigned to the Wasatch formation rest upon the Navajo sandstone (Jurassic ?); concerning the folds in the Kaiparowits region, Gregory and Moore[36] state: "The monoclinal folds affect all the rocks from the uppermost Cretaceous downward but do not involve the Tertiary"; and on both flanks of the De Chelly upwarp in northeastern Arizona

Rafael Swell, Emery, Wayne, and Garfield Counties, Utah," *U. S. Geol. Survey Bull.* (in preparation).

[34] E. M. Spieker and J. B. Reeside, Jr., "Cretaceous and Tertiary Formations of the Wasatch Plateau, Utah," *Bull. Geol. Soc. America*, Vol. 36 (1925), p. 452.

[35] E. M. Spieker and J. B. Reeside, Jr., *op. cit.*, p. 450.

[36] H. E. Gregory and R. C. Moore, "The Kaiparowits Region," *U. S. Geol. Survey Prof. Paper 164* (1931), p. 118.

relatively flat-lying Eocene (?) rocks rest upon inclined older rocks.[37]

The Tertiary structural history of southeastern Utah can not be satisfactorily interpreted, because of the absence of rocks younger than the Eocene and because the Eocene rocks have been eroded from most of the region. The fragmentary evidence shows that regional crustal movement and local deformation associated with the intrusion of igneous rocks occurred during this period.

The Lower Eocene Wasatch formation and the Middle Eocene Green River formation were involved in the subsidence of the Uinta Basin, as shown by the basinward dipping strata along the Book Cliffs, which are on the south limb of the basin. Bradley[38] describes the occurrence of the Middle Eocene Bridger formation and the Upper Eocene Uinta formation in the center of the Uinta Basin, and concerning the age of the folding he states:

> The Uinta formation, of upper Eocene age, comprising the youngest rocks of the basin, took part in the major deformation, which is therefore post-Eocene. It may perhaps have been later than early Miocene and coincident with a partial collapse of the east end of the Uinta Mountain arch, which faulted and in places strongly flexed beds of the Browns Park formation.

The age of the Browns Park formation has been determined to be Upper Miocene or Lower Pliocene.[39]

Another important event in the Tertiary structural history of the region was the intrusion of igneous rocks, forming laccoliths that arched the overlying strata. The Henry, Abajo, and LaSal mountains and Navajo Mountain are of this type. Gilbert[40] described the laccoliths of the Henry Mountains and made an approximate calculation of the depth of cover at the time of intrusion, from which he concluded that:

> What evidence we have, then, indicates that the epoch of laccolithic intrusion was after the accumulation of deep Tertiary deposits and before the subsequent degradation had made great progress—that it was at or near the close of the epoch of local Tertiary sedimentation.

No thick deposits of Tertiary rocks younger than Eocene are known in the Plateau region, so that it seems probable that "the

[37] H. E. Gregory, "The Navajo Country," *U. S. Geol. Survey Prof. Paper 93* (1917), pp. 111–12.

[38] W. H. Bradley, "Origin and Microfossils of the Oil Shale of the Green River Formation of Colorado and Utah," *U. S. Geol. Survey Prof. Paper 168* (1931), p. 6.

[39] O. A. Peterson, "The Browns Park Formation," *Carnegie Mus. Mem.*, Vol. 11, No. 2 (1928), p. 88.

[40] G. K. Gilbert, "Geology of the Henry Mountains," *U. S. Geog. and Geol. Survey Rocky Mountain Region* (1877), p. 94.

close of the epoch of local Tertiary sedimentation" was near the end of the Eocene.

Numerous normal faults cut rocks of Eocene age at the western edge of the Plateau province, thus definitely placing their age as Tertiary, but their exact age in the Tertiary is unknown. Dutton[41] described these faults and concluded, principally from physiographic evidence, that the faulting was of Pliocene age or younger. Spieker and Reeside[42] suggest that the faults originated in the late stages of a great uplift of the region which probably took place in late Tertiary time.

A minor but very recent event in the structural history of the region is the development of normal faults and grabens along Colorado River near its junction with Green River. The poorly developed drainage through the area of graben faulting and well defined old drainage channels cut off by the faults shows that the faulting occurred after the surface had been eroded to essentially its present position. A recent fault which cuts a caliche-capped surface has been recognized near Salt Valley,[43] which suggests that similar recent small-scale faulting may be more widespread in the region than has been recognized.

ORIGIN OF STRUCTURE

As pointed out in the descriptions of the different structural features and in the discussion of the periods of deformation, the geologic structure of southeastern Utah presents many different types of structure that have been formed at different times and under different conditions of deformation. Most of the larger structural features were formed during the Laramide orogeny at the close of the Cretaceous; earlier crustal movements appear to have been, for the most part, of epeirogenic type which had little influence on the structural features formed during subsequent crustal movements. The Uncompahgre highland and some of the smaller folds near Moab are exceptions to this general statement, as they were already in existence and were either accentuated by the Laramide deformation or exerted an influence on the localization and habit of the Laramide folds. It is possible also that the warping near the end of the Mississippian, which resulted in the formation of the structural basin in

[41] C. E. Dutton, "Geology of the High Plateaus of Utah," *U. S. Geog. and Geol. Survey Rocky Mountain Region* (1880), p. 43.

[42] E. M. Spieker and J. B. Reeside, Jr., "Cretaceous and Tertiary Formations of the Wasatch Plateau, Utah," *Bull. Geol. Soc. America*, Vol. 36 (1925), p. 453.

[43] C. H. Dane, "Geology of the Salt Valley Anticline and Adjacent Areas, Grand County, Utah," *U. S. Geol. Survey Bull. 863* (in press).

which the Paradox formation was deposited, may have exerted some control in localizing the subsequently formed regional upwarps, but this possible effect can not be evaluated, because so little information concerning this early folding is available.

DEFORMATION AT CLOSE OF CRETACEOUS

The most prominent structural features formed during the Laramide orogeny are the huge asymmetrical folds, such as the Circle Cliffs upwarp and the San Rafael Swell. The general character of the folds with a northerly trend, gently dipping west flank, and steeply dipping east flank, suggests that the folds represent either flexing of the surface rocks over deep-seated normal faults with downthrow toward the east, or are the result of compressive forces acting in an east-west direction. That such compressive forces were operative at this time in the region lying west of the area under consideration is unquestionable, as testified by thrust faults with overriding movement toward the east and anticlines overturned toward the east in the vicinity of Mt. Nebo,[44] and similar deformation on the western side of the Wasatch Plateau.[45] Folds overturned toward the east and thrust faults with the movement of the overriding block toward the east are also prominent features of the geologic structure of southern Nevada. Although the time at which these structural features in Nevada originated can not be precisely determined, some reasons have been given for assigning them to a late Cretaceous or early Tertiary period of orogeny.[46] Similarly, folding and faulting in the mountain ranges of western Colorado offer abundant evidence of compressive forces operating at this time during the uplift of the Rocky Mountains.[47]

Some features of the large anticlinal upwarps in the Plateau region suggest an origin of these folds as the result of the action of compressive forces rather than vertical movement over normal faults in the substratum. Not all of the hypothetical normal faults would be expected to have displacements in the same direction, if the faults

[44] E. J. Eardley, "Structure of Physiography of the Southern Wasatch Mountains, Utah," *Michigan Acad. Sci. Papers, Arts and Letters*, Vol. 19 (1933), pp. 377–400.

[45] E. M. Spieker, in M. P. Billings, "Thrusting Younger Rocks over Older," *Amer. Jour. Sci.*, Vol. 25 (1933), pp. 153–55.

[46] D. F. Hewett, "Geology and Ore Deposits of the Goodsprings Quadrangle, Nevada," *U. S. Geol. Survey Prof. Paper 162* (1931), pp. 42–55.
C. R. Longwell, "Geology of the Muddy Mountains, Nevada," *U. S. Geol. Survey Bull. 798* (1928), pp. 105–23; "Structural Studies in Southern Nevada and Western Arizona," *Bull. Geol. Soc. America*, Vol. 37 (1931), pp. 573, 574.

[47] T. S. Lovering, "Geology of Colorado," *16th Internat. Geol. Congress Guidebook 19* (1933), pp. 19–25.

were tensional features, and not all of the large monoclines, therefore, would be expected to slope in one direction. The low tensile strength of rock suggests the inference that fracturing under tension would result in the formation of numerous small, closely spaced, normal faults, instead of the few widely spaced faults that would be expressed at the surface by the principal monoclines. At the north ends of the San Rafael Swell and the Monument and Kaibab upwarps the east-facing monoclines terminate by flattening as they swing westward around the ends of the upwarps, a condition which does not suggest a decrease in the amount of flexing of strata over a normal fault as the displacement of the fault decreases. The presence of subsidiary folds near the crests of some of the upwarps, and especially on the Monument upwarp, appear to be entirely in accord with a theory of origin involving compressive forces, but these folds probably could not have been formed if the crests of the upwarps were under tension as the result of vertical uplift over normal faults. It is therefore believed that the regional upwarps were not formed by vertical movement over deep-seated normal faults of a type that could be interpreted as representing tension in the earth's crust, but were formed by compressive forces.

These forces presumably acted in a general east-west direction, although the trends of the resulting folds range from northwest to northeast. So far as the writer knows, there are no satisfactory criteria to determine in this region whether the impelling stress came from the west or from the east. The conception of compressive stress applied from the west has been rather generally held and it is believed that this conception may be reasonably adopted for convenience of discussion.

If the existence of horizontal compression be accepted, alternative hypotheses may be advanced to account for the structural habit of the large upwarps. (1) The more competent basement rocks may have transmitted the stress for long distances and broken at a few lines of weakness, with resulting overthrust or steep reverse faults which did not extend to the surface but caused an arching of the less competent overlying sedimentary rocks; or (2) the basement rocks and the overlying sedimentary rocks may have been deformed by folding unrelated to thrust faulting. The writer is inclined toward the opinion that the greater part of the deformation in the sedimentary rocks is the result of arching of the strata above overthrust or steep reverse faults in the basement rocks. The subsidiary folds on the west limb of the Monument upwarp near the Utah-Arizona State

line are similar to the major upwarps and possibly reflect subsidiary faulting in the basement rocks.

Some features of the upwarps may be considered as offering slight evidence that the upwarps originated as flexures over deep-seated reverse faults, although this evidence does not entirely preclude other theories of origin. The large upwarps are few in number and they are conspicuously larger, both in areal extent and structural relief, than other folds in the region; the principal deformation occurred along a few lines of weakness and the relative movement is in the same direction along each of these lines. The long, gently dipping west limbs of the upwarps are in general only slightly modified by subordinate folding, a condition suggesting the rotation of a block along a curved reverse fault and that the surface rocks in the block were not subjected to intense pressure. Minor normal faults on the crest of the San Rafael Swell might fit into this theory as tensional features developed during the uplift, although similar faults are rare on the crests of the other upwarps; the normal faults on the crest of the San Rafael Swell appear to be an extension to the west of the fault system developed in the desert south of Green River, and therefore to have a similar origin (see p. 1505). If the upwarps were formed by rotational movement along reverse faults, the steep monoclinal belts forming the east limbs of the upwarps would be under tension and normal faults parallel to the strike might be expected. Gregory and Moore suggest the presence of a strike fault with downthrow toward the east along the East Kaibab monocline south of where it is crossed by Paria River,[48] and a strike fault is present along the same monocline farther south where it crosses Colorado River in northern Arizona.[49]

Thrust faults of proved or possible post-Cretaceous-pre-Tertiary age are present in the region on the west. A continuous zone of thrust faulting is not known to be present west of the entire area covered by the map—in fact, no thrust faults are known west of the greater part of the area, but it is possible that such faults are present in parts of this region where the geology has not been mapped in detail, or it is possible that in the latitude of the large upwarps the thrusts have been transmitted farther toward the east than in areas north and south of this latitude.

[48] H. E. Gregory and R. C. Moore, "The Kaiparowits Region, a Geographic and Geologic Reconnaissance of Parts of Utah and Arizona," *U. S. Geol. Survey Prof. Paper 164* (1931), p. 122.

[49] N. H. Darton, "A Résumé of Arizona Geology," *Univ. of Arizona Bull. 119* (1925), Pl. 52.

According to the reverse fault theory of origin of the regional upwarps, it appears to be necessary to ascribe the San Rafael Swell and the Circle Cliffs upwarp to two distinct reverse faults, with the northern end of the Circle Cliffs "reverse fault" overriding the southern end of the San Rafael block. The folds at the southern end of the swell, which trend in a direction more or less transverse to the axis of the swell but are approximately parallel to the trend of the axis of the Circle Cliffs upwarp, could be interpreted as due to compression in front of the overriding block.

Another phase of the crustal deformation, believed to be associated with the Laramide orogeny, that deserves brief discussion, is the origin of the unusual structural features in the region surrounding Moab. Because folds and faults of the type of the Salt Valley faulted anticline, Upheaval dome, and the Lisbon faulted anticline, are present only within the limits of the part of the state underlain by the Paradox formation (Fig. 3), and because of the intimate relation of the formation to many of these structural features, it is clearly evident that the origin of most of these features has been more or less directly controlled by the thick series of relatively plastic salt-bearing beds in the Paradox formation. The initial folding of some of the anticlines occurred after the deposition of the Permian Cutler formation, but younger formations, including the Mancos shale, of Upper Cretaceous age, are involved in the principal folding and faulting; it seems probable, therefore, that lines of weakness developed during the earlier folding served to localize at least some of the subsequent folding. The principal folds in this area are compressed in a northeasterly direction and their axial trend is parallel to the belt of crystalline rocks of the Uncompahgre-San Luis highland in western Colorado, which was a land mass during Pennsylvanian, Permian, and part of Triassic time.[50]

It seems evident that the rocks overlying the Paradox formation, and hence supported by relatively plastic rock, were crumpled against the buttress of crystalline rocks in the Uncompahgre-San Luis highland as a result of compressive forces associated with the Laramide orogeny; the resultant folds were oriented parallel to the buttress.

During the deformation of the region the salt-bearing beds of the Paradox formation were under considerable pressure. Because of the plastic nature of these rocks, they would tend to flow under the pressure, which would be transmitted, therefore, more or less as

[50] A. A. Baker, C. H. Dane, and J. B. Reeside, Jr., "Paradox Formation of Eastern Utah and Western Colorado," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 8 (August, 1933), p. 974.

hydraulic pressure, to all sides of the enclosing chamber. Locally, as at several places along the Salt Valley faulted fold, the pressure on the salt beds caused them to intrude the overlying rocks, perhaps at a late stage in the arching of the anticlines, forming elongate salt domes. Intrusion to a lesser degree probably occurred at this time also in Moab Valley, at Upheaval dome, and possibly in small domes along Colorado River below the mouth of Green River. Many of the small anticlines and synclines in this region probably represent minor buckling and adjustment, under compressive forces, of the rocks overlying the Paradox formation, without involving intrusion of the salt into overlying rocks, but accompanied by flowage of the salt from beneath synclines into the upward arching anticlines. Subsequent erosion has weakened the roof locally over the salt beds and the pressure on the salt due to the weight of the overlying rocks in the adjacent region has caused the plastic salt to arch and in some places to rupture the weakened cover. These features are particularly well shown in the vicinity of the junction of Green and Colorado rivers where the rocks along the canyon bottom are arched and locally ruptured, and the plateau surface adjoining the canyon of Colorado River has been lowered in very recent geologic time by both graben faulting and a downward sagging.

Upheaval dome, which has been described by McKnight,[51] is a sharp dome surrounded by a narrow ringlike syncline. It appears to be a salt dome in which the salt has not been uncovered by erosion and a dome of the type produced experimentally and described by Nettleton.[52]

The numerous small normal faults in the area between the crest of the San Rafael Swell and the Utah-Colorado State line are located principally within the area underlain by the Paradox formation. They may have been formed during a period of readjustment after the regional pressure had been relieved, or they may be related in origin to regional folding as developed toward the west and south of them, or, as seems most probable, they may be evidence of strain in the block of sediments which overlies the plastic Paradox formation and which was compressed by a force directed from the west against the northwestward trending Uncompahgre highland.

DEFORMATION DURING TERTIARY

The crustal deformation that occurred during the Tertiary is of

[51] E. T. McKnight, "Geology and Oil Resources of Portions of Grand and San Juan Counties, Utah," *U. S. Geol. Survey Bull.* (in preparation).

[52] L. L. Nettleton, "Fluid Mechanics of Salt Domes," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 18, No. 9 (September, 1934), pp. 1175–1203.

three types: (1) formation of the mountains of laccolithic origin, (2) normal faulting in a zone lying near and beyond the west boundary of the map, and (3) downwarping of the Uinta Basin. Whether these structural features are more or less contemporaneous in origin, or, if they are not contemporaneous, the relative order of their occurrence in the Tertiary structural history of the region, can not be determined because of the incomplete sequence of Tertiary strata. In the absence of evidence bearing on possible genetic relationship, it is necessary to treat the origin of these features as separate events, although it is recognized that there may have been a direct relationship between them, both in time and the nature of the crustal deformation which they represent.

The mountains of laccolithic origin in southeastern Utah include the Henry, LaSal, and Abajo mountains and Navajo Mountain. These mountain masses are similar in origin and structure and are believed to have been formed at the same time. However, they are 40–50 miles apart and have no obvious alignment which might suggest localization along lines of crustal weakness. Gould[53] has described the geology of the LaSal Mountains and, in discussing the origin of the mountains, he ascribes considerable importance to the rôle of orogenic stresses in controlling their formation. He cites the association of some of the laccoliths of the LaSal Mountains with anticlinal folds, such as the Spanish Valley and Salt Valley folds in Utah, and the Paradox anticline in Colorado, as evidence that compressive forces were operative at the time of intrusion. However, it is the writer's opinion, as presented on preceding pages, that these folds were formed during the Laramide orogeny and therefore antedated the laccolithic mountains by a period equal at least to the greater part of the Eocene. The folding or doming associated with all of the other laccolithic mountains in Utah is confined to the mountain masses and shows no relation to the surrounding regional structure that would suggest regional compressive stresses during the formation of the mountains. The regional upwarps have exhibited no evident control over the location of the different laccolithic mountain groups, as each group when considered as a unit is differently located with respect to regional upwarps. Navajo Mountain is located slightly west of the crest of a low fold that is a southern continuation of the Circle Cliffs upwarp. The Henry Mountains are located on the gently westward dipping flank of the Monument upwarp east of the syncline adjacent to the Water Pocket monocline. The Abajo Mountains are

[53] L. M. Gould, "The Geology of LaSal Mountains of Utah," *Michigan Acad. Sci., Papers, Arts and Letters* (1927), pp. 103–05.

located in and immediately east of the syncline at the foot of the Comb monocline, which forms the east flank of the Monument upwarp. The LaSal Mountains are not associated with any of the large regional upwarps, but, as already mentioned, are in the midst of several smaller faulted folds. As pointed out by Gilbert, the local character of the uplift involved in the laccolithic mountains and the lack of any apparent relation of the structure of these mountains to the regional structure indicate that the doming of the strata overlying the intrusion is due to vertical upward pressure exerted by the intruding molten rock.[54]

The zone of Tertiary normal faults forming the west boundary of the plateau type of structure is the eastern limit of the normal faulting so common in the Great Basin. The normal faults at the eastern edge of the province, which in general have their downthrown side toward the west, but in part limit graben blocks, appear to accord with a hypothesis of regional uplift accompanied by a certain amount of collapse or sagging.[55] The great amount of erosion that has occurred in the Plateau region since the last thick Tertiary formations were deposited and the physiographic evidence of uplift afforded by the existence of remnants of old erosion surfaces prove that uplift has occurred in the region during several periods in the Tertiary, and it appears probable that at least part of the uplift in the Plateau region was contemporaneous with the uplift of the Great Basin on the west. The reasons for collapse with the development of normal faults in only part of the uplifted region are not clear, but the suggested collapse toward the west may be related in some way to the vast amount of igneous activity, both extrusive and intrusive, which has occurred in that region.

The Uinta Basin appears to have been a relatively stable area during the Tertiary uplift that affected the region on the west and south. It may have risen, but to a lesser degree, during the uplift of the adjacent region, or there may have been slight downward movement during the general uplift.

[54] G. K. Gilbert, "Geology of the Henry Mountains," *U. S. Geog. and Geol. Survey Rocky Mountain Region* (1877).

[55] B. S. Butler, "The Ore Deposits of Utah," *U. S. Geol. Survey Prof. Paper 111* (1920), pp. 104–05.

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FREDERICKSBURG GROUP OF LOWER CRETACEOUS WITH SPECIAL REFERENCE TO NORTH-CENTRAL TEXAS[1]

SHERIDAN A. THOMPSON[2]
Dallas, Texas

ABSTRACT

The Edwards limestone, Comanche Peak limestone, and Walnut clay are reduced to the status of members of one formation, which is given the name Gatesville from the type locality near the State Training School for Boys north of Gatesville, Coryell County, Texas. The Fredericksburg group is shown to include only two formations, the Kiamichi clay and the Gatesville. It is separated from the overlying Washita group in North-Central Texas and Southwest Texas by an unconformity, but in West Texas in Pecos County there is no indicated break in sedimentation. The contact with the underlying Trinity group is unconformable on the margins of the Comanche basin, while outward in the basin continuous deposition appears to have been maintained from uppermost Trinity into Fredericksburg.

History of Nomenclature

The first observations of Cretaceous rocks in Texas were made in the early part of the nineteenth century by travelers passing westward through the country. The writings of these people were fragmentary. The first real contributions to the subject were by the German geologist Ferdinand Roemer, who visited Texas from 1845 to 1847 for the purpose of studying the desirability of the state for German settlement. In the course of this study Roemer made many valuable geological observations. In 1846[3] and again in 1848[4] he published papers on the geology of Texas in the *American Journal of Science*. In 1849[5] he published in German a volume concerning Texas with especial reference to German emigration and the physical conditions of the country based on his own observations. He followed

[1] Presented before the Association at the Dallas meeting, March 22, 1934. Manuscript received, July, 29, 1935.

[2] Magnolia Petroleum Company.

[3] Ferdinand Roemer, "A Sketch of the Geology of Texas," *Amer. Jour. Sci.*, 2nd Ser., Vol. 2 (1846), pp. 358–65.

[4] Ferdinand Roemer, "Contributions to the Geology of Texas," *ibid.*, Vol. 6 (1848), pp. 21–28.

[5] Ferdinand Roemer, *Texas. Mit besonderer Rücksicht auf deutsche Auswanderung und die physichen Verhältnisse des Landes nach eigener Beobachtung geschildert. Mit einem naturwissenschaftlichen Anhange und einer topographisch-geognostichen Karte von Texas.* Bonn, bei Adolph Marcus (1849).

this in 1852 with that monumental work commonly known as the *Kreidebildungen of Texas*.[6] In this publication he did not name any formations, but classified the rocks as of Upper Cretaceous age and grouped them into "Beds at the foot of the Highlands" and "Beds of the Highlands" with what is now known as the Balcones fault scarp as the basis for the division. Roemer regarded the beds forming the escarpment as younger than those at its foot. This error is easily understood in the light of history by the fact that at that time the existence of the Balcones fault was not known, though in justice to Roemer it should be stated that in his later writings he suggested its possibility.

G. G. Shumard made the next important contribution on the Cretaceous of Texas in 1854.[7] This was based on work done two years earlier, when he was attached as geologist to an expedition by the United States Army for the exploration of the Red River of Louisiana. He named the beds which he mapped from Fort Washita, Oklahoma, to Fort Belknap, Young County, Texas, the Fort Washita limestone. B. F. Shumard prepared that part of the report which described the fossils collected. As was the general practice at the time, they were considered Upper Cretaceous in age.

Until 1855 no one had recognized any Lower Cretaceous in North America, but in that year Jules Marcou[8] identified some fossils collected from Texas and western Oklahoma as Neocomian and stated that rocks of that age occupied large areas in both Texas and Indian Territory. This conclusion was no doubt based largely on the observations made by Marcou when he accompanied an expedition known as the "Thirty-Fifth Parallel Survey"[9] sent by the Federal Government a few years previously to locate a suitable route for a railroad to the Pacific Coast. This route followed approximately the course of the South Canadian River across Oklahoma and the Panhandle of Texas. On account of a misunderstanding with the War Department, Marcou did not write a report, but his notes were given to W. P. Blake, who

[6] Ferdinand Roemer, *Die Kreidebildungen von Texas und ihre organischen Einschlüsse. Mit einem die Beschreibung von Versteinerungen aus paläozoischen und tertiaren Schichten enthaltenden Anhange und 11 mit von C. Hohe nach der Natur auf Stein gezeichneten Tafeln*. Bonn, bei Adolph Marcus (1852).

[7] *Expl. Red River of Louisiana in the Year 1852*, by R. B. Marcy, Captain 5th Infantry, United States Army, assisted by Geo. B. McClellan, Brevet Captain United States Engineers; with report on the natural history of the country and numerous illustrations. Washington (1854).

[8] *Pacific Railroad Expedition Reports*, Vol. 4 (1855), pp. 40–48. Republished in the 4th edition of Marcou's *Geology of North America* (1858).

[9] *Reports of Explorations and Surveys to Ascertain the Most Practicable and Economical Route for a Railroad from the Mississippi River to the Pacific Ocean, Made under the Direction of the Secretary of War, 1853–1854–1855*, Vol. 3, Washington (1856).

prepared the geologic section of the official report. It is also probable that some of the material was derived from a second similar expedition, known as the "Thirty-Second Parallel Survey," which crossed Texas from the vicinity of Denison to El Paso. Marcou did not accompany this expedition but had access to the notes and collections of the officers, from which he wrote a brief general report.[10] Like most newly advanced ideas in geology, the existence of Lower Cretaceous in North America was not immediately accepted and it was only after many controversies that it came to be generally accepted.

In 1858 B. F. Shumard was appointed State geologist of Texas but was relieved of his duties in 1860. Investigations made by himself and others during and prior to his brief term of office formed the basis of an important paper published in 1860 in the *Transactions* of the St. Louis Academy of Science.[11] In this paper Shumard was the first to name, describe, and assemble into a section a series of formations of the Cretaceous of Texas. Like Roemer, he made the error of reversing the normal order of the sediments, such as considering the Austin chalk older than most of the Comanche rocks, due to his failure to recognize the Balcones fault-scarp. His formations were the *Caprina* limestone, Comanche Peak group, and *Caprotina* limestone, all of which were considered Upper Cretaceous in age. The *Caprina* limestone, which later was called Edwards limestone, he described as

> a yellowish-white limestone, sometimes of a finely granular texture, and sometimes made up of rather coarse, subcrystalline grains, cemented with chalky paste. It generally occurs in thick massive beds and is usually found capping the highest elevations.

His brief description of the Comanche Peak group was:

> soft, yellowish and whitish, chalky limestone, and buff and cream colored limestones of greater or less compactness.

The *Caprotina* limestone was described as

> light gray and yellowish gray, earthy limestone, with intercalated bands of yellow marl, and sometimes flint.

The fossil list which he submitted for this formation and his description of the lithology clearly indicate Shumard was dealing with that part of the section which is now recognized as the Glen Rose formation.

[10] Bvt. Captain John Pope, Corps of Top. Eng. "Geological Notes of a Survey of the Country Comprised between Preston, Red River, and El Paso, Rio Grande del Norte, in Report of Exploration of a Route for the Pacific Railroad near the Thirty-Second Parallel of Latitude, from Red River to the Rio Grande," *Report of Secretary of War, House Document 129*, Vol. 4, Chap. 13 (1855) pp. 125–28.

[11] B. F. Shumard, "Observations upon the Cretaceous Strata of Texas," *Trans. Acad. Sci., St. Louis*, Vol. 1 (1860), pp. 582–90.

Following the year 1860, during the Civil War and the dark days of reconstruction, there were few contributions of importance to the subject of the Cretaceous geology of Texas. Then in 1887 there appeared that remarkable observer, R. T. Hill, who made a study of the rocks from Elmo, Kaufman County, Texas, to Millsap, Parker County, Texas, along the Texas and Pacific Railroad right of way. He was the first to recognize the proper sequence of the Cretaceous formations of Texas. The results of this field work appeared in a paper in the *American Journal of Science* in 1887.[12] In this paper Hill correctly showed the Comanche series as belonging to the Lower Cretaceous and underlying the Middle and Upper Cretaceous. In studying the rocks west of Fort Worth he observed that they carried a fauna identical with that which Roemer had described 35 years before in his *Kreidebildungen von Texas* from the rocks around the town of Fredericksburg. He, therefore, gave the name of Fredericksburg division to this group and the name of Washita division to those rocks east of Forth Worth up to the sands which are now called Woodbine. Hill used the formation names given by Shumard[13] in 1860 and placed the top of the Fredericksburg at the top of a zone of "*Ammonites acutocarinatus* Shumard." The base of his Washita was described as "ferruginous, calcareous marls" and with "forniculate and naviate varieties of *Gryphea pitcheri* abundant." *Gryphea pitcheri* Morton is now regarded as the same as *Gryphea corrugata* Say.[14] From the lithologic and paleontologic descriptions it appears that beds which are now recognized as Kiamichi clay were considered basal Washita, though in later writings Hill stated it was his first intention to place the Kiamichi clay in the Fredericksburg. Regardless of this point, Hill's Fredericksburg included all rocks downward in the section to the base of the *Caprotina* limestone of Shumard or the Glen Rose as it is now known. The sand beneath the Glen Rose was called the Dinosaur sand or upper Cross Timber sand and was not included in his Comanche series. At that time Hill was apparently uncertain as to its age and could not decide whether it should be considered Cretaceous or Jura-Triassic.

From this time forward Hill worked with a feverish determination to obtain a clearer understanding of the Comanche section. In the capacity of assistant state geologist of Arkansas he published in the

[12] R. T. Hill, "The Topography and Geology of the Cross Timbers and Surrounding Regions in North Texas," *Amer. Jour. Sci.* (3) 33:291–303, map (1887).

[13] B. F. Shumard, *op. cit.*, pp. 582–90.

[14] W. S. Adkins, "Handbook of Texas Cretaceous Fossils," *Univ. Texas Bull. 2838* (1928), p. 107.

Annual Report of the Arkansas Geological Survey of 1888[15] a comprehensive paper on the geology of southwestern Arkansas. Except for a preliminary notice published in *Science* (January 13, 1888), Hill named and described in this paper for the first time the Trinity division. He clearly recognized a non-marine sand and mottled clay section at the top with a limestone and gypsum series underneath and another sand and gravel section at the base resting unconformably on the Paleozoic rocks. It is quite evident this is the same sequence which is now recognized as the Paluxy sand, the Glen Rose formation, and the Basement sands. This classification placed beds equivalent to the Dinosaur sands of Texas in the Trinity and restricted the Fredericksburg in Arkansas as it was first defined by transferring beds equivalent to the *Caprotina* limestone (present Glen Rose) of Texas from basal Fredericksburg to upper Trinity. Hill correctly stated that the Trinity was the lowest Mesozoic exposed in the area, but he was still uncertain whether it should be assigned to the Cretaceous or the Jura-Triassic.

In the following year Hill became associated with the Texas State Geological Survey and published a paper[16] in the first annual report of the Survey based principally upon a study of a preliminary section along the Colorado River from near Smithwick Mills, Burnet County, to Webberville, Travis County. In this study he introduced the names Trinity sands and Travis Peak sands of the Trinity division as referring to those sands lying unconformably on top of the Paleozoic rocks. Recently he has stated[17] that these two names, as well as Dinosaur sand, Western Cross Timbers sands, and Basement sands, refer to the same series of rocks. Even though in the Arkansas report he placed beds equivalent to the *Caprotina* limestone (present Glen Rose) in the upper Trinity, it is doubtful if he recognized the equivalency, since in the Texas report he again placed the *Caprotina* limestone in the basal Fredericksburg.

Of the many early papers which Hill produced, the paper published in 1891[18] was probably his second most important contribution to the subject of Comanche geology. In this paper he definitely placed the Kiamichi in the Washita. The top of the *Caprina* limestone of Shumard was considered as the top of the Fredericksburg, and

[15] R. T. Hill, "The Neozoic Geology of Southwestern Arkansas," *Ann. Rept. Geol. Survey of Arkansas*, Vol. II (1888).

[16] R. T. Hill, "Brief Description of the Cretaceous Rocks of Texas and Their Economic Uses," *1st. Ann. Rept. Geol. Survey of Texas* (1889), pp. 105–41.

[17] Personal communication by letter, February 14, 1934.

[18] R. T. Hill, "The Comanche Series of the Texas-Arkansas Region" (with Discussion by C. A. White and Others), *Bull. Geol. Soc. America*, Vol. 2 (1891), pp. 503–28.

Comanche Peak chalk was used for Shumard's Comanche Peak group except in southern Oklahoma, where the name Goodland limestone was given to its northern extension. This is the first appearance of this name (Goodland) in the literature. Beneath the Comanche Peak chalk and well exposed around the town of Walnut Springs in Bosque County, Texas, is a group of sediments, "overlying and underlying *Gryphea* beds," which Hill named in this paper, Walnut clays. He described them as "alternating strata of thin limestone flags and yellow clay marls, accompanied by inconceivable numbers of *Exogyra texana*, Roemer." The yellow color is characteristic of the surface exposures only. In wells the clay is black. Hill also named and described for the first time in this paper the Paluxy sands and tentatively assigned them to the Fredericksburg. The name Glen Rose was substituted for *Caprotina* limestone, which was no longer considered Fredericksburg in age, but the youngest formation of the Trinity. The term Trinity sands was still used for the sands and gravels at the base of the Trinity division. While Hill classified the Trinity as belonging to the Comanche series, he still felt it had more Jurassic than Cretaceous paleontologic affinities.

The next important contribution to the subject of Fredericksburg geology was a joint paper by Hill and Vaughan in 1897.[19] In this paper the name Edwards limestone was substituted for *Caprina* limestone without change of definition to avoid the use of a faunal name. The term Travis Peak formation was used for the basal sandy section of the Trinity division.

Then in 1900, after 13 years of persistent investigation, Hill produced his monographic report on the "Geography and Geology of the Black and Grand Prairies of Texas,"[20] which has been a reference work for more than a quarter of a century for all students of Comanche geology. His final classification of the Fredericksburg was as follows.

Washita Division	Kiamichi clay	
Fredericksburg Division	Edwards limestone Comanche Peak limestone Walnut formation	Goodland limestone of Oklahoma (Edwards limestone, Comanche Peak limestone)
Trinity Division	Paluxy formation Glen Rose formation Travis Peak formation	Antlers sands of North Texas

[19] R. T. Hill and T. W. Vaughan, "Geology of the Edwards Plateau and Rio Grande Plain Adjacent to Austin and San Antonio, Texas, with Reference to the Occurrence of Underground Waters," *18th Ann. Rept. U. S. Geol. Survey*, Pt. II (1897), pp. 193–322.

[20] R. T. Hill, "Geography and Geology of the Black and Grand Prairies, Texas, with Detailed Descriptions of the Cretaceous Formations and Special Reference to Artesian Waters," *21st Ann. Rept. U. S. Geol. Survey*, Part VII (1899–1900).

The Kiamichi was retained in the Washita. The Paluxy was definitely placed in the Trinity and the Walnut in the Fredericksburg,

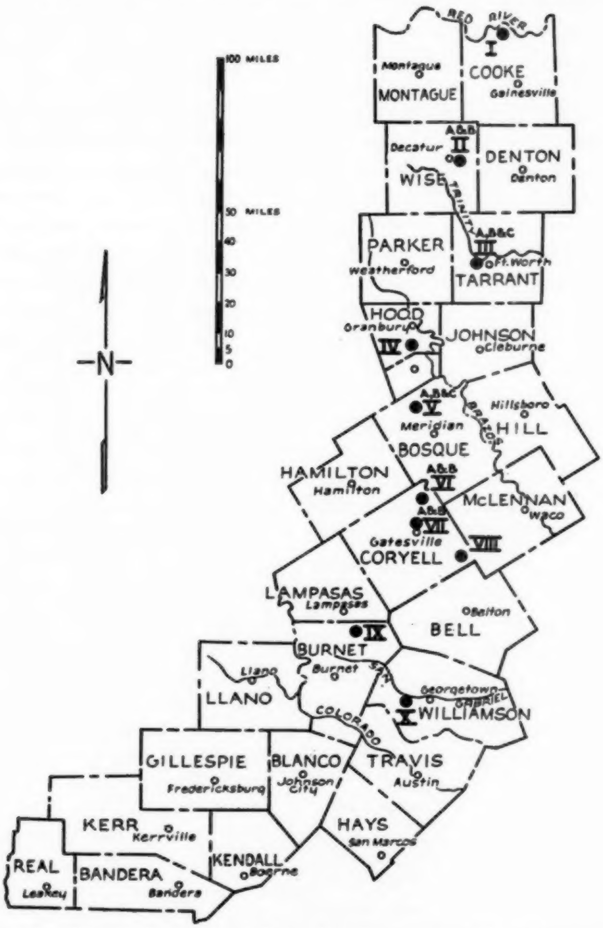

FIG. 1.—Map of North-Central Texas showing general position of measured sections.

but it was stated that from Wise County northward the Walnut passes horizontally into the Basement (Antlers) sands of the Trinity.[21] Apparently Hill had been unable to draw a sharp boundary between

[21] R. T. Hill, *op. cit.*, p. 207.

the Trinity and Fredericksburg. This was one of the few problems which he left for later investigators.

Stratigraphy

DESCRIPTIONS OF MEASURED SECTIONS

In order to understand the stratigraphy of the Fredericksburg of north-central Texas a series of sections was measured and studied from Red River southward to Williamson County, Texas. Each locality where one or more sections have been measured has been assigned a number. Where several sections have been measured near the same locality they have been designated by letters.

SECTION I

SECTION OF WHITE BLUFF ALONG RED RIVER, NORTHWEST OF SIVELLS BEND POST OFFICE, COOKE COUNTY, TEXAS

This section can be reached by traveling 1.3 miles west from the Sivells Bend Methodist Church and thence north 1.2 miles along the pipe line of

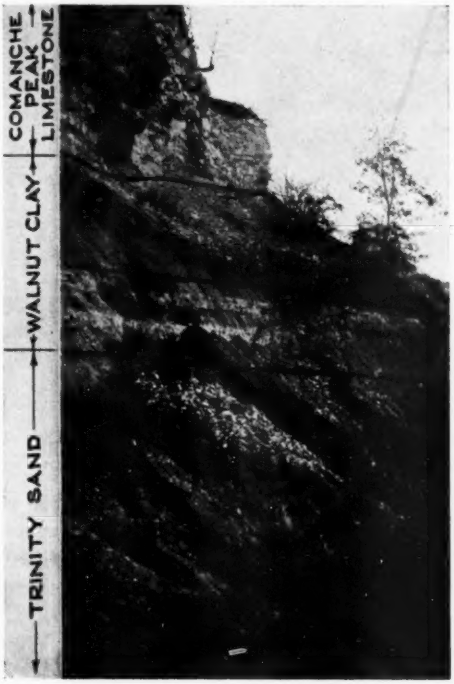

Plate 1.—White Bluff on Red River, Cooke County, Texas. Middle line marks base of upper 12 feet of non-calcareous shale in Walnut clay.

the Lone Star Gas Company to the bluff on the river where the best exposures appear about 1,000 feet east of the pipe-line crossing.

Duck Creek formation		
Kiamichi clay	*Feet*	
Poorly exposed—clay with limestones 1–6 inches thick composed of shell agglomerate. *Gryphea navia* Hall abundant. Limestones break down into blocks standing on edge in weathered clay....	35	
Comanche Peak limestone (Goodland limestone)	*Feet*	*Inches*
Alternating layers of white nodular and chalky limestone.......	23	6
White, nodular marl..	3	0
Brown, argillaceous marl weathering white....................	1	0
Total	27	6
Walnut clay	*Feet*	*Inches*
Black-to-brown, non-calcareous shale with a few particles of lignite	12	0
Shell agglomerate containing many *Exogyra texana* Roemer......	0	8
Black-to-brown, calcareous, arenaceous shale.................	1	3
Sandy limestone..	1	0
Brown-to-black, nodular marl and shale containing *Exogyra texana* Roemer, a very small amount of glauconite, an abundance of shell and echinoid fragments and microfossils determined by C. I. Alexander as follows. *Cythereis fredericksburgensis* Alexander; *Cythereis mahonae* Alexander; *Cythereis subgoodlandensis* Vanderpool; *Cythereis carpenterae* Alexander; *Cytheridea* aff. *bairdioides* (Cornuel); *Cytheridea* spp.; *Eocytheropteron* aff. *semiconstrictum* Alexander; *Cytherella fredericksburgensis* Alexander; *Cytherelloidea rhomboidea* Vanderpool; *Ammobaculites subgoodlandensis* Vanderpool; *Vaginulina intumescens* Reuss............................	4	3
Brown, argillaceous marl with irregular grains of dark green glauconite. Contact at base is uneven with worm borings into sand below filled with marl...	0	3
Total	19	5
Trinity sand (Antlers sand) (upper part)	*Feet*	*Inches*
Argillaceous sand..	1	0
Black-to-brown, non-calcareous, carbonaceous clay............	3	0
Sand slightly argillaceous...................................	2	6
Pack sand with indurated layers and variegated clays..........	153	0
Total exposed	159	6

This section has been described by H. P. Bybee and Fred M. Bullard,[22] but these authors did not recognize any Walnut. They considered all the rocks below the Comanche Peak (Goodland) as belonging to the Trinity sand. According to Hill's[23] original definition of the Walnut, it is composed of two facies of rock, namely, flaggy

[22] H. P. Bybee and Fred M. Bullard, "The Geology of Cooke County, Texas," *Univ. Texas Bull. 2710* (1927), pp. 12–13.

[23] R. T. Hill, "The Comanche Series of the Texas-Arkansas Region" (with Discussion by C. A. White and Others), *Bull. Geol. Soc. America*, Vol. 2 (1891) p. 512.

limestones and yellow clay marls associated with shell agglomerates. A careful study of these sediments over wide areas reveals that the limestones and shell agglomerates predominate at the base and the yellow clay marls at the top. In the White Bluff section the limestone and shells are found in the basal portion, but the typical upper yellow clay marl is represented by 12 feet of black-to-brown, non-calcareous shale. This upper part is mappable into the yellow clay marl farther

PLATE 2.—Contact of Walnut clay and Trinity (Antlers) sand at White Bluff on Red River, Cooke County, Texas. Above contact are marl and shell fragments. Note worm borings in Trinity sand below.

south and the change toward the north is interpreted as a shoreward facies. The presence of shell agglomerate in the lower part with glauconite in 3 inches of marl above the wavy contact at the base and the worm borings into the Trinity sand below indicate a sharp break in sedimentation. This break is considered a good basis for drawing the line between the Fredericksburg and Trinity at this horizon.

SECTION II A
SECTION 0.7 MILE WEST OF COURTHOUSE AT DECATUR, WISE COUNTY, TEXAS

This section is located where the old road leading west from the south side of courthouse square crosses the escarpment 0.7 mile due west of the courthouse.

Comanche Peak limestone (Goodland limestone) (lower part)	*Feet*
Indurated shell agglomerate	1
Soft, white, nodular marl	5
Total exposed	6

Walnut clay	Feet
Yellow, arenaceous clay marl grading upward into white marl. *Gryphea marcoui* Hill and Vaughan	13
Indurated shell agglomerate composed of three layers separated by clay ranging from 6 inches to 1 foot in thickness. Top layer forms persistent bench	6
Yellow, arenaceous clay marl with an abundance of *Gryphea marcoui* Hill and Vaughan and *Exogyra texana* Roemer	21
Total	40

Paluxy sand—Pack sand

The contact at the base of the Walnut with the underlying Paluxy is abrupt, but does not reveal any wavy characteristics. This is evidently a local condition, as elsewhere in Wise, Tarrant, and Montague counties, Scott and Armstrong[24] report:

> The base of the Walnut often presents a wavy contact with the Paluxy. The lowest stratum is composed of gravelly sand filled with fossils, but there are no fossils below this bed. In places the contact level is replaced by a sandy plant bed which is literally filled with broken, reworked pieces of lignitized wood.

SECTION II B

CATLETT CREEK SECTION 9.3 MILES EAST OF DECATUR, WISE COUNTY, TEXAS

This section is located 0.7 mile east of where Texas State Highway No. 24 from Decatur to Denton crosses Catlett Creek and 1.2 miles north of this highway on a lateral road.

Kiamichi clay
Poorly exposed

Comanche Peak limestone (Goodland limestone)	Feet
Nodular-to-massive, white limestone	7
Alternating white marl and nodular limestone, forming bench at top	13
Alternating white marl and nodular limestone, hard layer at top	12
Alternating white marl and nodular limestone, top forms indistinct bench	3
Poorly exposed—white marl with many shells at top and nodular at base	5
Total	40

Walnut clay	Feet
Arenaceous, yellow clay marl	13
Indurated shell agglomerate, forms very prominent bench at top	27
Total	40

Paluxy sand—Pack sand

The Kiamichi was not measured at this locality, but 3.5 miles farther east where the State highway crosses the Wise-Denton County line it is approximately 30 feet thick. It is composed essentially of

[24] Gayle Scott and J. M. Armstrong, "The Geology of Wise County, Texas," *Univ. Texas Bull. 3224* (1932), p. 53.

clay with some shell agglomerates and some arenaceous limestones which break down into slabs that stand on end on the clay slopes. This feature has given rise to the local name of "edge rock" wherever the formation has been well developed. *Gryphea navia* Hall is the most characteristic fossil and the most abundant species in the shell agglomerates.

SECTION III A

SECTION AT EAST END OF BRIDGE OF TEXAS STATE HIGHWAY NO. 34 CROSSING LAKE WORTH, TARRANT COUNTY, TEXAS

	Feet	Inches
Comanche Peak limestone (Goodland limestone)		
White, chalky, nodular limestone		
Walnut clay	*Feet*	*Inches*
Yellow-to-brown clay marl grading upward into chalky limestone	16	0
White limestone grading downward into shell agglomerate	0	6
Shell agglomerate in indurated layers, top forms prominent bench. *Gryphea marcoui* Hill and Vaughan and *Exogyra texana* Roemer abundant	23	0
Calcareous, fossiliferous clay with wavy contact at base and worm borings filled with same material in sand below	0	6
Total	40	0
Paluxy sand (upper part)	*Feet*	*Inches*
Argillaceous sand containing small amount of lignite	1	6
Pack sand	4	0
Total exposed	5	6
Water level		

The upper yellow-to-brown clay marl of the Walnut is best exposed about 1,500 feet north of the highway near the edge of the lake.

SECTION III B

SECTION AT LAKE WORTH DAM ON NORTH SIDE OF LAKE, TARRANT COUNTY, TEXAS

This locality can be reached by turning off Texas State Highway No. 34, 2.3 miles east of the bridge crossing the lake and traveling southeast 0.7 mile. A car can be driven to the edge of the cliff and a trail leads down to the dam near which the section can be studied.

Duck Creek formation	
Kiamichi clay	*Feet*
Brown clay containing *Gryphea navia* Hall and limestones 3–6 inches thick	37
Comanche Peak limestone (Goodland limestone)	
Alternating white, chalky limestone and marl in layers ranging from 6 inches to 7 feet thick	70
Covered	26±
Total	96±

Walnut clay (upper part)	*Feet*	*Inches*
Covered	16±	0
Yellow-to-brown clay marl	0	6
White limestone	1	0
Shell agglomerate	9	0
Total exposed	26±	6

PLATE 3.—Exposure of Comanche Peak limestone 70 feet high at Section III B near Lake Worth dam, Tarrant County, Texas. Note ledges of hard, white, chalky limestone with intervening soft marl. Base of Kiamichi clay is at top of exposure.

SECTION III C

WESTOVER HILLS SECTION, FORT WORTH, TEXAS

This section is on the north side of Byers Street, 1.1 miles northwest of its intersection with Camp Bowie Boulevard, Texas State Highway No. 1.

Duck Creek formation (lower part)	*Feet*
Limestone, nodular-to-massive	15
Limestone (*Hamites* ledge)	7
Total exposed	22

	Feet
Kiamichi clay	
Brown clay with several sandy limestones ranging from 2 inches to 1 foot thick. *Gryphea navia* Hall abundant. At top are a few chert pebbles underneath overlying limestone of Duck Creek containing many fucoids in its base	40
Comanche Peak limestone (Goodland limestone) (upper part)	
White, chalky limestone and marl	50

This locality is the only place where pebbles have been observed at the contact of the Kiamichi and the Duck Creek. Even here they are rare and it is only after the most diligent search that they can be found.

The Comanche Peak maintains its characteristic facies at this exposure, but about 10 miles southwest of Fort Worth on United States Highway No. 377 near Benbrook, Taff[25] found a rudistid in its upper 4 feet. Since rudistids are characteristic of the Edwards farther south, this has been considered a shoreward extension of the Edwards facies. C. E. Decker is reported to have discovered a rudistid deposit in the Fredericksburg 1.5 miles west of Valliant, McCurtain County, Oklahoma.[26] It is quite possible this locality is about the same distance from the old shore as the Benbrook area and that its exposure should be assigned to the Edwards also.

SECTION IV

SECTION OF COMANCHE PEAK, HOOD COUNTY, TEXAS

This section was measured on the south side of the peak 6 miles southwest of Granbury on the Granbury-Brushy and Hill City road.

	Feet
Edwards limestone (lower part)	
Gray, hard, massive, rudistid-bearing limestone	25±
Comanche Peak limestone	
Alternating white, chalky limestone and marl. Fossils abundant, in places forming shell agglomerates	104

Walnut clay	Feet	Inches
Yellow clay marl with sandy limestone 3 inches thick near top	2	0
Brown limestone, forming bench	0	6
Yellow clay marl with ledges of gray limestone 3–6 inches thick	16	0
Brown, platy, sandy limestone, forming bench	0	1
Yellow clay marl	6	0
Alternating gray, marly limestone and yellow clay marl	9	0
Yellow clay marl containing an abundance of shells. *Gryphea marcoui* Hill and Vaughan and *Exogyra texana* Roemer	16	0
Indurated shell agglomerate, forming bench	17	0
Yellow clay marl	0	2
Calcareous sand with wavy contact and reworked fossils at base	0	4
Total	67	1

[25] Joseph Alexander Taff and S. Leverett, "Report on the Cretaceous Area North of Colorado River, Texas," *Texas Geol. Survey Ann. Rept. 4*, Pt. 1 (1893), pp. 239–354, maps.

[26] W. S. Adkins, "The Geology of Texas, Vol. I, Stratigraphy, Part 2, The Mesozoic System in Texas," *Univ. Texas Bull. 3232* (1933), p. 339, and personal communication from Gayle Scott.

Paluxy sand	*Feet*	*Inches*
Pack sand	0	2
Shale	0	2
Pack sand poorly exposed	117±	0
Total	117±	4

Glen Rose formation

SECTION V A

SECTION ON COLEY MORRIS FARM 2.1 MILES SOUTHWEST OF WALNUT SPRINGS, BOSQUE COUNTY, TEXAS

This section is located 2.1 miles southwest of Walnut Springs and about 0.4 mile north of Texas State Highway No. 174 from Walnut Springs to Iredell.

PLATE 4.—Contact of Walnut clay and Paluxy sand at Section V A 2.1 miles southwest of Walnut Springs, Bosque County, Texas. The two lines include 1 foot of clay containing glauconite and a sand lens. Note its variation in thickness and uneven contact at base.

Comanche Peak limestone (lower part)	*Feet*	*Inches*
Top of low butte		
White, chalky limestone	21	
Walnut clay		
Yellow-to-brown, fossiliferous limestone	0	6
Yellow clay marl with thin, platy, sandy limestones	12	0
Gray-to-yellow marl	10	0
Covered	30	0
Indurated shell agglomerate, forming bench and containing many *Gryphea marcoui* Hill and Vaughan and *Exogyra texana* Roemer.	4	0
Yellow clay marl and shell agglomerate containing *Gryphea marcoui* Hill and Vaughan and *Exogyra texana* Roemer	7	0
Yellow clay marl and shell agglomerate, forming bench at top and containing *Gryphea marcoui* Hill and Vaughan and *Exogyra texana* Roemer	21	0
Hard limestone with ripple marks at top, containing an abundance of shells and weathering brown-to-gray in color	7	0

Clay with glauconite and sand lens inclusion 3 inches thick. Uneven contact at base. Poorly preserved microfossils determined by C. I. Alexander as follows.		
Cythereis fredericksburgensis Alexander		
Cythereis mahonae Alexander		
Eocytheropteron sp.	1	0
Total	92	6
Paluxy sand (upper part)	*Feet*	*Inches*
Pack sand	0	6
Sandy shale	0	4
Pack sand	10	0
Total exposed	10	10

This section includes all the rocks from the top of the low butte to the bed of Little or East Bosque Creek. Near the city park of Walnut Springs and on the south side of Steel Creek that part of the lower Walnut is exposed which is described as covered on the Coley Morris farm. It is essentially a yellow clay marl with 2 feet of alternating yellow clay marl and gray limestone lying immediately above the shell agglomerate.

SECTION V B

SECTION ON TEXAS STATE HIGHWAY NO. 174 FROM WALNUT SPRINGS TO IREDELL, 3.4 MILES SOUTHWEST OF WALNUT SPRINGS, BOSQUE COUNTY, TEXAS

Walnut clay	
Paluxy sand	*Feet*
Argillaceous sand and shale with calcareous nodules	30
Glen Rose formation	

SECTION V C

SECTION ON SOUTH SIDE OF TEXAS STATE HIGHWAY NO. 174 FROM WALNUT SPRINGS TO IREDELL, 2.5 MILES SOUTHWEST OF WALNUT SPRINGS, BOSQUE COUNTY, TEXAS

Edwards limestone (lower part)	*Feet*
Top of cap rock	
Hard, rudistid-bearing limestone	25±
Comanche Peak limestone	
White, chalky limestone weathering into resistant ledges with intervening soft gray-to-white marl	137
Walnut clay—yellow clay marl	

SECTION VI A

SECTION 6.5 MILES NORTHEAST OF TURNERSVILLE ON TURNERSVILLE-CLIFTON ROAD, CORYELL COUNTY, TEXAS

Duck Creek formation (lower part)	*Feet*
Limestone and marl, containing *Desmosceras brazoense* (Shumard), poorly exposed	
Limestone, containing *Hamites*	7
Kiamichi clay	
Yellow-to-brown clay containing few scattered grains of glauconite and *Exogyra texana* Roemer	
Microfossils collected 10 feet below top determined by C. I. Alexander as follows.	

Cythereis fredericksburgensis Alexander	
Cythereis mahonae Alexander	
Flabellammina alexanderi Cushman	25
Edwards limestone	
Massive limestone containing rudistids and chert, poorly exposed	

SECTION VI B

SECTION ALONG CREEK SOUTH OF ROAD CROSSING CREEK FLOWING THROUGH EAST SIDE OF TOWN OF TURNERSVILLE, CORYELL COUNTY, TEXAS

	Feet
Duck Creek formation (lower part)	
Limestone containing *Hamites* and with sharp contact at base	8
Kiamichi clay	
Nodular marl, containing *Gryphea navia* Hall	7
Marly clay and shale	6
Total	13
Edwards limestone (upper part)	
Alternating sandy limestones 2–6 inches thick and marly clays 1–4 inches thick	7
Massive, cherty limestone in creek bed	

SECTION VII A

SECTION 5.3 MILES NORTH OF GATESVILLE ON TEXAS STATE HIGHWAY NO. 36 FROM GATESVILLE TO TURNERSVILLE, CORYELL COUNTY, TEXAS

	Feet
Duck Creek formation (lower part)	
Limestone containing *Hamites*	5
Kiamichi clay	
Buff marl containing *Gryphea navia* Hall near top. Upper contact very sharp	12
Edwards limestone (upper part)	
Limestone, containing rudistids	5
Argillaceous marl	5
Massive limestone	
Total exposed	10

This section includes those rocks from the top of the escarpment downward 10 feet into the Edwards. A few specimens of *Desmosceras brazoense* (Shumard) were found lying loose above the basal limestone ledge of the Duck Creek on top of the escarpment.

SECTION VII B

SECTION NEAR STATE TRAINING SCHOOL FOR BOYS ON TEXAS STATE HIGHWAY NO. 36 ABOUT 3.6 MILES NORTH OF GATESVILLE, CORYELL COUNTY, TEXAS

	Feet	Inches
Duck Creek formation (lower part)		
Limestone with angular fracture containing *Hamites* and *Desmosceras brazoense* (Shumard)	4	
Kiamichi clay		
Buff marl containing *Gryphea navia* Hall	5	
Edwards limestone		
Hard, massive limestone, containing rudistids	17	
Comanche Peak limestone		
White, chalky limestone with hard and soft layers	89	
White, chalky limestone with hard and soft layers, forms bench at top	52	
Total	141	

Walnut clay		
Yellow clay marl with thin buff-to-gray limestones. Poorly exposed. Measured in fields northeast of State Training School....	44	0
Shell agglomerate containing abundance of *Gryphea marcoui* Hill and Vaughan, forms prominent bench........................	4	0
Yellow clay marl with thin buff-to-gray limestones. *Gryphea marcoui* Hill and Vaughan abundant.........................	39	0
Gray-to-buff, fossiliferous limestone with ripple marks at top, striking N. 45° W..	12	0
Poorly exposed fossiliferous limestones and yellow clay marl, containing *Gryphea marcoui* Hill and Vaughan and *Exogyra texana* Roemer..	25	0
Gray, nodular limestone, containing *Exogyra texana* Roemer....	0	6
Shale containing shell and echinoid fragments and a few scattered grains of glauconite. Contact at base is uneven. Microfossils determined by C. I. Alexander as follows. *Cythereis fredericksburgensis* Alexander, *Cytherella fredericksburgensis* Alexander, *Flabellammina alexanderi* Cushman..........................	0	1
Total	124	7

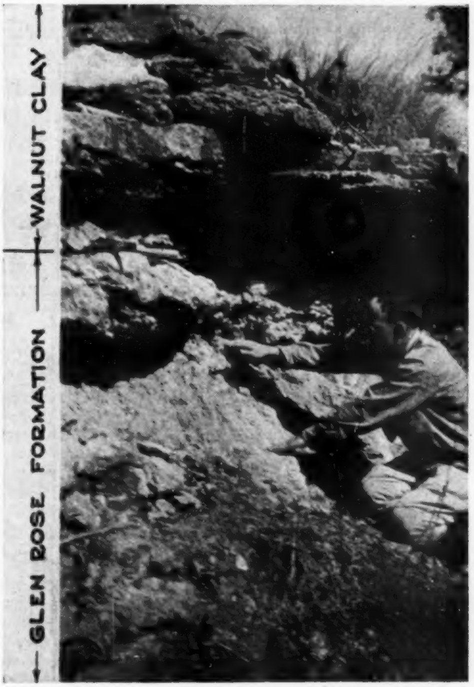

PLATE 5.—Contact of Walnut clay and Glen Rose formation at Section VII B near State Training School for Boys about 3.6 miles north of Gatesville, Coryell County, Texas. Between contact and right hand of figure is stratum of sandy limestone 10 inches thick with oysters at base. Between hands of figure is stratum of argillaceous sand 15 inches thick.

Glen Rose formation (upper part)		
Sandy limestone with oysters at base, *Ostrea franklini* var. *ragsdalei* Hill. Microfossils determined by C. I. Alexander as follows.		
Cytheridea aff. *amygdaloides* (Cornuel)		
Eocytheropteron trinitense (Vanderpool)		
Cytheridea aff. *amygdaloides*; var. *brevis* (Cornuel)		10
Argillaceous sand		15
Fossiliferous limestone	2	0
Covered	10	0
Pack sand	1	0
Total exposed	15	1
Bottom of gully		

The State Training School buildings stand on top of the shell agglomerate, which is 44 feet below the top of the Walnut. The contact between the Glen Rose and Walnut may be found in a gully about 2,000 feet due west of the school, with good exposures of basal Walnut in the intervening area. The upper 44 feet of the Walnut is not well exposed, but can be seen best in the fields below the escarpment northeast of the school. The best exposures of the Comanche Peak, Edwards, Kiamichi, and Duck Creek can be reached by traveling 0.4 mile north of the State Training School on Texas State Highway No. 36 to a point where it turns west, and from that point continuing due north 1.9 miles on a lateral road to the escarpment, which is capped by the Duck Creek of the basal Washita.

SECTION VIII

SECTION AT EAGLE SPRINGS, CORYELL COUNTY, TEXAS, ABOUT 17 MILES EAST AND SLIGHTLY SOUTH OF GATESVILLE WHERE THE GATESVILLE-MOODY ROAD CROSSES ONION CREEK NORTH OF A CHURCH

	Feet
Duck Creek formation (lower part)	
Top of bench	
Limestone with angular fracture, containing *Hamites*, *Desmosceras brazoense* (Shumard) in upper 6 feet and *Mortoniceras trinodosum*[27] (Böse) near top. At base is buff marl 0–6 inches thick forming wavy contact	10
Edwards limestone (upper part)	
Massive limestone, containing rudistids and forming waterfall	15

SECTION IX

SECTION OF BACHELOR PEAK 7.5 MILES SOUTHEAST OF LAMPASAS AND 2,000 FEET NORTH OF TEXAS STATE HIGHWAY NO. 74, BURNET COUNTY, TEXAS

	Feet
Comanche Peak limestone (lower part)	
White, chalky, nodular limestone	46
Marly limestone weathering yellow	2
Total exposed	48
Walnut clay	
Shell agglomerate, *Gryphea marcoui* Hill and Vaughan	5

[27] This was formerly considered *Pervinquieria trinodosa* (Böse) and previous to that *Schloenbachia trinodosa* Böse.

Yellow clay marl and limestone, containing *Gryphea marcoui* Hill and Vaughan, *Exogyra texana*, Roemer. Contact gradational at base	35
Yellow, nodular limestone, containing *Exogyra texana* Roemer and *Trigonia*. Contact gradational at base	48
Yellow clay marl and limestone, containing *Exogyra texana* Roemer and *Gryphea marcoui* Hill and Vaughan	2
Gray-to-white limestone, forming bench	1
Yellow clay marl and limestone, containing *Exogyra texana* Roemer and *Gryphea marcoui* Hill and Vaughan	5
Gray-to-white limestone	2
Yellow clay marl, containing *Exogyra texana* Roemer and *Gryphea marcoui* Hill and Vaughan	5
Gray limestone	2
Buff, fossiliferous marl, containing *Exogyra texana* Roemer and some small *Gryphea marcoui* Hill and Vaughan	4
Nodular marl with uneven contact at base	1
Total	110
Glen Rose Formation (upper part)	
Fine, cross-bedded sand slightly argillaceous	5
Yellow, argillaceous sand	8
Very argillaceous, gray limestone	4
Total exposed	17

SECTION X

SECTION 3 MILES NORTHWEST OF LEANDER WHERE TEXAS STATE HIGHWAY NO. 29 CROSSES SOUTH SAN GABRIEL RIVER, WILLIAMSON COUNTY, TEXAS

Comanche Peak limestone (lower part)	*Feet*	*Inches*
Top of butte about 2,000 feet west of highway		
White, chalky limestone with hard and soft layers	19	
Shell agglomerate, containing an abundance of *Gryphea marcoui* Hill and Vaughan	5	
White, chalky limestone with hard and soft layers containing an abundance of *Gryphea marcoui* Hill and Vaughan	22	
Total exposed	46	
Walnut clay		
Yellow clay marl and limestone. Microfossils determined by C. I. Alexander as follows.' *Cythereis fredericksburgensis* Alexander; *Cythereis carpenterae* Alexander; *Cytherella fredericksburgensis* Alexander; *Ammobaculites goodlandensis* Cushman and Alexander	32	
White-to-gray limestone with hard and soft layers marly near base and containing many *Trigonia*. Microfossil determinations by C. I. Alexander same as foregoing with addition of *Lituola* sp. (This is the Cedar Park member of Adkins.)[28]	80	
Buff, sandy limestone containing *Exogyra texana* Roemer. Microfossils determined by C. I. Alexander as follows. *Cythereis fredericksburgensis* Alexander; *Cythereis* aff. *wintoni* (?); *Lituola* sp.; *Flabellammina alexanderi* Cushman	5	
Alternating hard and nodular limestone containing *Exogyra texana* Roemer, and slight amount of glauconite. Microfossils determined by C. I. Alexander as follows.		

[28] W. S. Adkins, *op. cit.*, p. 331.

Cythereis fredericksburgensis Alexander		
Cythereis subgoodlandensis Vanderpool		
Haplostiche sp.	12	
Bluish, nodular limestone. Microfossils determined by C. I. Alexander as follows.		
Cythereis fredericksburgensis Alexander		
Cytheridea spp.		
Eocytheropteron spp.	3	
Total	132	
Glen Rose formation (upper part)		
Sandy limestone with pockets 10 inches in diameter filled with celestite. Top is pitted and suggests mud cracks		6
Sandy limestone	2	
Water level		
Total exposed	2	6

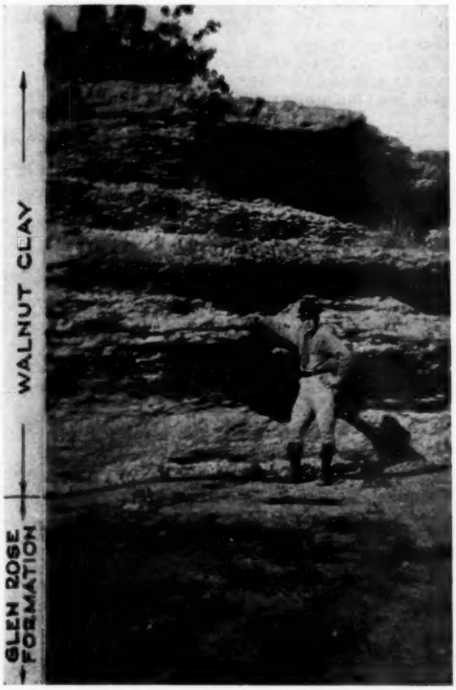

PLATE 6.—Contact of Walnut clay and Glen Rose formation at Section X on South San Gabriel River 3 miles northwest of Leander, Williamson County, Texas. Note pitted appearance of ledge on which man is standing.

About 0.5 mile upstream from this locality an additional 2 feet of the Glen Rose is exposed. It is composed of arenaceous and argillaceous limestone containing lignite fragments.

Adkins' Cedar Park member of the Walnut appears to be a local development, although the yellow, nodular limestone 40 feet below the top of the Walnut at Bachelor Peak is probably its equivalent.

DISCUSSION OF CORRELATIONS

LIMITS OF FREDERICKSBURG GROUP

The columnar sections which appear in Figure 2 were prepared to vertical scale from the measured sections, but no attempt was made to show individual details except to indicate some of the generalized facies of the Walnut and Comanche Peak members. The term "group" has been substituted for "division" in conformity with the rules of nomenclature and classification adopted in 1933 by the Association of State Geologists, the United States Geological Survey, the American Association of Petroleum Geologists, and the Geological Society of America.[29]

All rocks from the base of the Walnut to the top of the Kiamichi have been placed in the Fredericksburg group. This classification is supported both by the paleontology and the field relationships. The ammonites, *Oxytropidoceras* and *Diploceras*, according to Adkins,[30] began their development at the beginning of Walnut time and flourished until the end of Kiamichi time, when they disappeared. They were followed, especially in North Texas, by an almost explosive development in the Duck Creek of entirely different groups of ammonites representing many genera and species. This restricted occurrence of the ammonites is certainly a sound paleontological basis for defining the limits of the Fredericksburg. The variation in thickness of the Kiamichi in North Texas and its complete absence farther south indicate that it was subjected to erosion. The presence of the pebbles at the contact of the Kiamichi and Duck Creek in the Westover Hills section (Section III C) at Fort Worth strengthens the argument for a break in sedimentation at this horizon. In this connection it is important to note that south from Coryell County, where the Kiamichi is absent, the Edwards shows considerable porosity, whereas farther north it is more dense. This suggests that the porosity may be due to a post-Fredericksburg but pre-Washita erosion which removed all the impervious Kiamichi before establishing solution channels in the Edwards. In West Texas in Pecos County there is no evidence of any unconformity at the top of the Kiamichi, which has a thickness of about 66 feet. This is 50 per cent greater than its average thickness in North Texas. In the lower part are *Oxytropidoceras*, and in the middle,

[29] *Bull. Geol. Soc. America*, Vol. 44 (1933), pp. 423–59.

[30] W. S. Adkins, *op. cit.*, pp. 325–26.

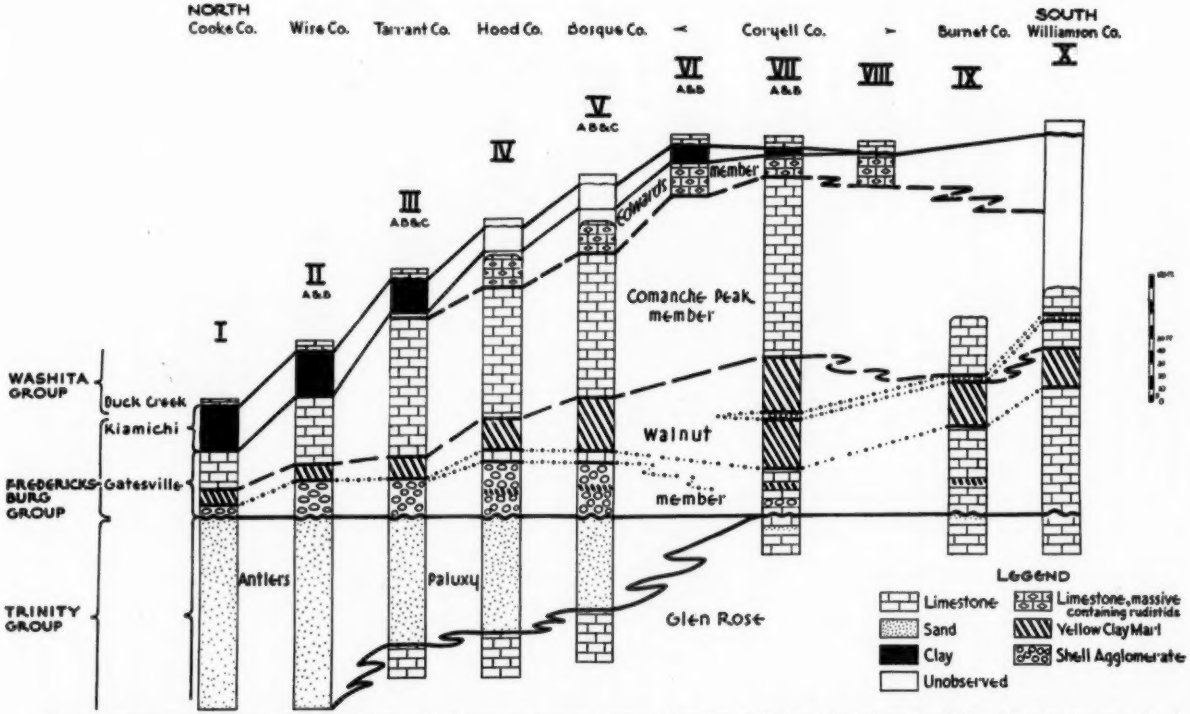

FIG. 2.—Columnar sections from Red River to Williamson County, Texas. *I*. Section of White Bluff along Red River, Cooke County. *II*, *A* and *B*. Section near Decatur, Wise County. *III*, *A*, *B*, and *C*. Section near Fort Worth, Tarrant County. *IV*. Section of Comanche Peak, Hood County. *V*, *A*, *B*, and *C*. Section near Walnut Springs, Bosque County. *VI*, *A* and *B*. Section near Turnersville, Coryell County. *VII*, *A* and *B*. Section near State Training School for Boys at Gatesville, Coryell County. *VIII*. Section at Eagle Springs, Coryell County. *IX*. Section of Bachelor Peak, Burnet County. *X*. Section on South San Gabriel River, Williamson County.

above a brown limestone 2 feet thick, are the typical ***Gryphea navia*** Hall. In the upper part there is an association of ***Elobiceras, Hamites,*** and ***Mortoniceras,***[31] in beds which Adkins[32] named post-Kiamichi. He stated that the ***Hamites*** and ***Mortoniceras*** continue to survive into the overlying Duck Creek, but that the ***Elobiceras*** do not. It is possible that Adkins' post-Kiamichi of Pecos County may be represented in North Texas by the erosion interval at the top of the Kiamichi.

The contact of the Walnut and the underlying Trinity group is uneven throughout North-Central Texas. The basal 3–6 inches of the Walnut is composed of glauconitic clay and occasionally fossiliferous gravelly sand which fill worm borings in the Paluxy sand of the underlying Trinity. This clearly indicates that there was a break in sedimentation at this horizon, which is probably no greater than a diastem.[33] Consequently, from the standpoint of both the fauna and the stratigraphy, the limits of the Fredericksburg are well placed.

FORMATIONAL AND INTRAFORMATIONAL CONTACTS

Lithologically the Kiamichi is essentially clay, the Edwards hard massive limestone, the Comanche Peak white, chalky limestone and gray marl, and the Walnut yellow clay marl in the upper part and shell agglomerate in the lower. The most difficult boundary to fix is the Walnut-Comanche Peak, which is decidedly gradational. In the interest of consistency and to avoid confusion, the author has arbitrarily placed all the section containing essentially yellow clay marl in the Walnut and reserved for the Comanche Peak that part which consists principally of white, chalky limestone. While it is true that shell agglomerates are characteristic of the Walnut, especially in the lower part, they do occur in the Comanche Peak and for this reason can not be used as the distinguishing feature of the Walnut. The boundary between the Comanche Peak and the Edwards is also gradational, and rarely will two competent observers place it at the same point. The contact between the Edwards and the Kiamichi is much sharper and can be mapped in the field with reasonable precision.

GATESVILLE FORMATION

LITHOLOGY AND THICKNESS

The sections in Figure 2 show that the Walnut and the Comanche Peak thicken basinward toward the south, neither at the expense of

[31] Regarded by some authors as *Pervinquieria.*

[32] W. S. Adkins, "The Geology and Mineral Resources of the Fort Stockton Quadrangle," *Univ. Texas Bull. 2738* (1927), p. 41.

[33] J. Barrell, "Rhythms and the Measurement of Geologic Time," *Bull. Geol. Soc. America*, Vol. 28 (1917), p. 794.

the other but both in about the same proportions. The same is true of the Edwards, but to a much less degree. All three represent one sedimentary unit composed of three different facies with vertical gradational boundaries. In Figure 2, in Section IX at Bachelor Peak in Burnet County the Walnut is thinner than in Sections VIII and X, but this is explained by the fact that Section IX is located closer to the old shore.

As the rocks comprising the Walnut-Comanche Peak-Edwards unit are traced basinward, the white, chalky limestone of the Comanche Peak is found to transgress downward in the section by lateral gradation of the Walnut facies to the Comanche Peak facies until finally the unit is composed of the upper massive rudistid-bearing limestone of Edwards facies and the underlying white, chalky limestone of Comanche Peak facies. In like manner, the Edwards basinward is found to transgress downward in the section by lateral gradation of the Comanche Peak facies to the Edwards facies so that finally the entire unit is composed of massive rudistid-bearing limestone of Edwards facies, as shown in Figure 3.

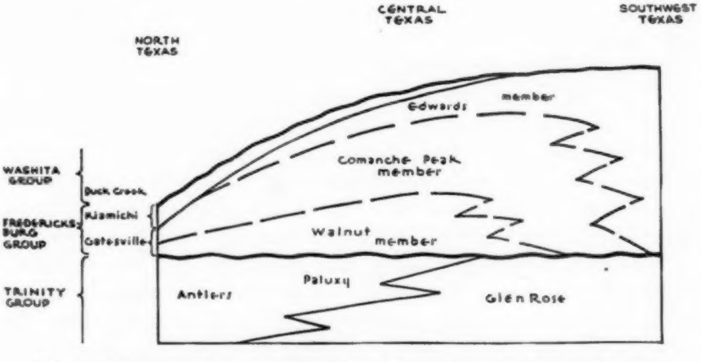

FIG. 3.—Diagrammatic cross section from North Texas to Southwest Texas.

In West Texas, in eastern Dawson and northwestern Borden counties, there are exposed the Walnut, Comanche Peak, and Edwards, each with their characteristic facies. The same changes in facies and thickness occur farther south as in North-Central Texas. In northern Martin County the Comanche Peak has transgressed downward in the section by lateral gradation of the Walnut facies to the Comanche Peak facies to such an extent that very little of the Walnut remains. At Big Spring, in Howard County, the downward transgression by lateral gradation of the Walnut facies to the Comanche

Peak facies has been complete and the Walnut is absent, with only the Edwards and the underlying Comanche Peak present. There is a shell agglomerate in the upper part of the white, chalky, nodular limestone of the Comanche Peak at this locality, but this is not uncommon in the Comanche Peak in areas where it is rapidly grading laterally into rocks of Walnut facies. This condition was observed at South San Gabriel River in Williamson County (Section X). Farther south in West Texas, in eastern Pecos County, the massive Edwards has transgressed downward by lateral gradation of the Comanche Peak facies to the Edwards facies to such an extent that the entire unit is composed entirely of rocks of the Edwards facies. At some places there are a few inches of marl or sandy limestone resembling the Walnut facies at the very base of the Edwards. However, in general the entire formation may be said to be composed of the hard, massive, rudistid-bearing limestone of Edwards facies.

PALEONTOLOGY

The Edwards, Comanche Peak, and Walnut possess essentially the same fauna. The most outstanding form is *Oxytropidoceras acutocarinatum* (Shumard). This is in marked contrast to *Oxytropidoceras belknapi* (Marcou) and *Gryphea navia* Hall, which first appear in the overlying Kiamichi.

The fauna of the Trinity is fairly distinctive, but little is known of the fossil zonation. In Travis County, about 15.5 miles west of Austin and 2.2 miles north of Bee Cave, on the road from Bee Cave to Lohmann's Crossing of Colorado River, there are good exposures of Trinity and Lower Fredericksburg where many of the larger fossils, such as *Exogyra texana* Roemer, *Loriolia texana* (Clark), and *Porocystis globularis* (Giebel) range from Trinity into Fredericksburg. C. I. Alexander reports that there is a similar range of the microfauna based on forms obtained from a series of samples collected from the same locality. This extension of Trinity fauna upward into the Fredericksburg around Austin indicates that sedimentation from Trinity to Fredericksburg must have been practically continuous in this area. In North Texas, where there is good evidence of a break in sedimentation between the Trinity and Fredericksburg, this upward range of many of the Trinity forms into the Fredericksburg has not been reported.

NAME

As has been shown, basinward there is a transgression downward in the section of the Comanche Peak by lateral gradation of the Walnut facies to the Comanche Peak facies, and of the Edwards by

lateral gradation of the Comanche Peak facies to the Edwards facies (Fig. 3). This condition has brought about confusion in the use of the names Walnut, Comanche Peak, and Edwards. Edwards, as originally defined, referred to the hard, massive, rudistid-bearing limestone on top of the white, chalky limestone of the Comanche Peak. Later, in areas where the massive limestone was found to have transgressed downward by lateral gradation of the white, chalky limestone to the massive, rudistid-bearing limestone so that the massive, rudistid-bearing limestone occupied the whole section to the top of the Trinity, it was still called Edwards. This has resulted in a name being applied to the whole of a formation in one locality and to a part of it in another. To correct this and to eliminate the confusion, it is proposed to reduce the status of the names of Walnut, Comanche Peak, and Edwards to the rank of members or facies of a single formation but at the same time retain their original definitions. The name Gatesville formation is here introduced and includes the Walnut, Comanche Peak, and Edwards members. The type locality is 3.6 miles north of Gatesville, Coryell County, near the State Training School for Boys, where all three members are exposed with their characteristic facies and have been described under Section VII B. This classification assigns only two formations, Gatesville and Kiamichi, to the Fredericksburg group. The two differ in fauna and lithology and the lithologic contact between them is reasonably sharp. It is proposed that in the future the name Goodland limestone be abandoned, as it is merely a synonym for Comanche Peak limestone, which has priority in the literature by more than 30 years.

GEOLOGIC HISTORY

TRINITY EPOCH

Beginning with Trinity time, the country was tilted toward the northwest, with the encroachment of the sea over the rugged Paleozoic rock floor. As the shore line advanced northwestward, sand and gravel were deposited on the basement floor, while the argillaceous and arenaceous limestone of the Glen Rose was deposited basinward and transgressively upward in the section toward the shore by lateral gradation to the Antlers sand as far north as Wise County (Section II A and B and Fig. 2). This is the most northwesterly extension of the Glen Rose in Texas and probably marks the time of the end of the advance of the Trinity sea. From this date forward the country was tilted back toward the southeast and the sea receded, leaving a low flat topography on the northwest and depositing the Paluxy sand farther and farther southeast with the result that it transgressed upward in the section

by lateral gradation to the limestone of the Glen Rose as far southeast as Coryell County (Section VII B and Fig. 2). Beyond this point the recession was less rapid because in Williamson County there is little evidence of any break in sedimentation at the top of the Trinity except for minor oscillations of the strand line, which will probably furnish ample grounds for endless argument as to the exact location of the Fredericksburg-Trinity contact. It is difficult to determine the exact point where the sea finally ceased to retreat. Travis County is the only area observed on the outcrop where sedimentation appears to have been continuous from Trinity to Fredericksburg. This is explained by the fact that, with the exception of an area in southern Hudspeth County,[34] this is the most basinward exposure of the Trinity-Fredericksburg contact that is known in Texas. The shore line was no doubt a little northwest.

FREDERICKSBURG EPOCH

At the beginning of Fredericksburg time the country was again tilted toward the northwest and the sea once more began its northwestward advance, this time over the low flat topography of the Paluxy sand. Wave-marked banks of shells were piled along the beach, later to be covered with yellow clay marl of the upper part of the Walnut as the sea gradually crept landward. This time it swept beyond the limits to which the Trinity sea had formerly advanced.[35] Figure 2 shows that its sediments thinned toward the shore on the northwest as they continued to overlap onto the Trinity rocks and finally onto the Paleozoic floor of Oklahoma. With this thinning northwestward there is the usual change in each formation to a shoreward facies on the extreme margins of the basin for which the observer must always be prepared. The location of the center of the basin is not known. It could have been about the same as the Rio Grande embayment of Southwest Texas. The Kiamichi clay represents the close of the Fredericksburg epoch and reveals a change from the conditions which produced the limestone facies of the underlying Gatesville. Apparently there was not a repetition of the gentle tilting at the close of the Fredericksburg epoch which had occurred through Trinity and early Fredericksburg time, but a more unequal distribution of movement. There was sufficient uplift to bring the Kiamichi out of the water, because of its complete erosion in Central and Southwest Texas and its partial erosion in North Texas, but in West Texas in the vicinity of

[34] Personal communication from W. S. Adkins.

[35] W. S. Adkins, "The Geology of Texas, Vol. I, Stratigraphy, Pt. 2, The Mesozoic Systems in Texas," *Univ. Texas Bull. 3232* (1933), p. 277.

Pecos County there was more crustal stability and deposition continued uninterruptedly into Washita time. Following this erosion the sea again covered the land, transgressing northwestward and depositing rocks of the Washita group.

CONCLUSIONS

The contact of the Fredericksburg and the Washita is placed at the top of the Kiamichi. The contact of the Fredericksburg and the Trinity is considered to represent a diastem near the margin of the Comanche basin, but continuous deposition is believed to have existed within the basin.

The Fredericksburg is divided into two formations: the Kiamichi and the Gatesville. The names Edwards limestone, Comanche Peak limestone, and Walnut clay, are retained with their original definitions but are reduced to the status of members of the Gatesville formation. They are distinct mappable units in North-Central Texas only as far south as Gatesville.

The name Goodland limestone is a synonym for the name Comanche Peak limestone, which has priority by approximately 30 years. It is contended this name (Goodland) should be abandoned.

ACKNOWLEDGMENTS

Appreciation is expressed to the Management of the Magnolia Petroleum Company and George Edwin Dorsey for providing the means for making this study and extending permission for its publication. Grateful acknowledgments are due Gayle Scott, W. S. Adkins, B. Coleman Renick, and Roy T. Hazzard for their helpful suggestions and encouragement. C. I. Alexander has generously given his aid in identifying the microfauna. Appreciation is also expressed to W. Brantley Jackson and William H. Winckler for their assistance in the preparation of the several drawings.

DISCUSSION

J. B. LOVEJOY, Fort Worth, Texas (written discussion received, August 1, 1935): Mr. Thompson's paper has more firmly fixed in my mind the thought that here there exists a problem which merits considerable study and attention. In this regard it has occurred to me that the paper has an air of finality with respect to the subdivisions of the Fredericksburg group and the delineations of the group proper which, when published, will have the weight of authority.

Through correspondence with Mr. L. P. Teas, I have been indirectly advised that Dr. Adkins does not agree that the Fredericksburg should be broken up as indicated in this paper, but that if it were broken up at all, it should be zoned on the bases of the relatively slight faunal changes. Dr.

Gayle Scott, of Texas Christian University, is of the opinion that the faunal changes as worked out by Dr. C. I. Alexander and himself warrant the divisions set forth in Mr. Thompson's paper. Dr. Scott is further convinced that there are evidences which show a lack of conformity at the upper contact of the Kiamichi formation in the vicinity of the city of Fort Worth. Rounded pebbles have been taken from the upper contact, and washed material at this level shows much grit and transported debris. It will be noted that both Dr. Adkins, who advises that information on the contacts of the Kiamichi is meager, and Mr. S. A. Thompson accept this more or less local evidence as lithological criteria for placing the division of the two groups at the upper contact of this formation. Personally, it appears to me that in taking a step so definite, more effective evidence secured over a wide area should be presented, rather than the reiteration of these local data.

Since the principal students of this problem are agreed that Mr. Thompson's paper offers a contribution to the Fredericksburg stratigraphy with special reference to North Texas, my only comment is that the paper should be placed clearly in the position of opening the question for discussion, at least as it applies to areas other than North Texas, rather than placing it in the position of a closed issue for all of Texas.

W. C. MENDENHALL, Washington, D. C. (written discussion received, August 19, 1935): Some of the Survey geologists who have worked in the Comanche series are inclined to question whether the introduction of the new name Gatesville would not increase rather than eliminate the confusion caused by the misapplication of the stratigraphic names already in use.

In the first place, it is questioned whether Goodland is actually a synonym of Comanche Peak and should therefore be abandoned. It is true that Comanche Peak has been used in at least two senses, but Hill's restriction of the name to the limestone unit between the Walnut and the Edwards has been in general use for more than 35 years and should be preferable to the more vague first definition by Shumard. Goodland seems to be a useful name for the northern thin limestone of the Fredericksburg where the Edwards is either very thin or not recognizable as such.

It should be remembered also that the assignment of Kiamichi to the Fredericksburg rather than to the Washita is still considered a debatable question by some geologists.

The frequent misapplication of the terms Edwards, Comanche Peak, and Walnut is probably in part due to the fact that locally they have been applied to lithologic and paleontologic facies rather than to well defined stratigraphic units. For example, in Southwest Texas the limestone of Washita age comprising practically the entire equivalent of the Georgetown was long believed to be Edwards limestone and may still be so designated locally by some geologists, though Udden named it the Devils River limestone.

SHERIDAN A. THOMPSON: Dr. Hill, who is the author of the name Goodland, stated at the Dallas, 1934, meeting of the Association that the name Goodland is a synonym of Comanche Peak.

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GEOLOGICAL NOTES

GRAPHICAL METHOD FOR ELIMINATING REGIONAL DIP

Elimination of the regional dip from a contoured structural map reveals many features of the structure which are more or less obscured by the regional tilting. By use of the graphical method here described a regional dip can be eliminated very quickly, accurately, and with a minimum of labor. Convergence of beds can be handled in the same manner.

What is essentially the same method has been used by Levorsen for eliminating convergence,[1] but its application to regional dip may be new to enough of the *Bulletin* readers to justify publication of this note.[2]

Assuming that we have a structure-contour map, and assuming that the direction and amount of regional dip are known, the procedure is as follows.

First, on tracing paper, construct a grid representing the regional dip contoured on the same scale and with the same contour interval as the structure map. The strike of the grid lines will be the strike of the regional dip and their spacing will be the same as the distance on the scale of the map required for a drop of one contour interval.

Second, superpose this grid over the structure map.

Third, contour by connecting diagonally through the intersections of the structure contours with the grid lines. This automatically produces a contour map of the structure with the regional dip eliminated.

The method of contouring is illustrated by the accompanying map (Fig. 1). With a little practice the work can be done almost as rapidly

[1] A. I. Levorsen, "Convergence Studies," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), pp. 672–73.

[2] The method in common use for eliminating convergence is mathematical rather than graphical, the grid on the convergence sheet being used only for estimating the amount to be added to, or subtracted from, the figures on the structure map to correct for the convergence or regional dip. See:
W. T. Griswold and M. J. Munn, "Geology of Oil and Gas Fields in Steubenville, Burgettstown, and Claysville Quadrangles, Ohio, West Virginia, and Pennsylvania," *U. S. Geol. Survey Bull. 318* (1907).
M. J. Munn, "Sewickley," *U. S. Geol. Survey Atlas Folio 176* (1911).
Roswell H. Johnson and L. G. Huntley, *Principles of Oil and Gas Production*, 1st. ed. (John Wiley and Sons, Inc., New York, 1916), pp. 207–09.
A. W. Ambrose, "Underground Conditions in Oil Fields," *U. S. Bur. Mines Bull. 195* (1921), pp. 49–52.

as the lines can be drawn. Because all of the work is done on one map in Figure 1, the result is somewhat confusing, but in actual practice the grid lines are drawn lightly in pencil on tracing paper, the resulting contours on the tracing paper are inked, and the grid lines then erased, so that there is no confusion.

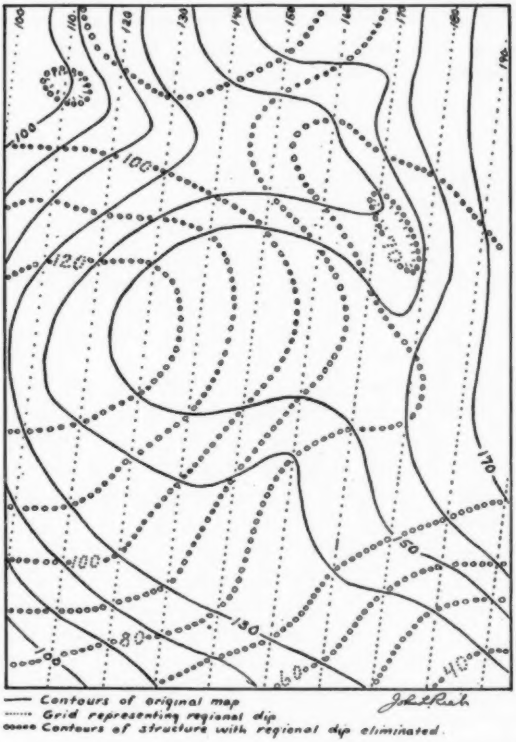

FIG. 1.—Map showing graphical method for eliminating regional dip.

The theory of the method is simple. Starting at a particular intersection of a grid line and a map contour, it is obvious that a line connecting that point with the intersection of the next higher contour with the next higher grid line must represent the position of a horizontal line if the land were to be tilted back so as to eliminate the regional dip.

Should it be desired to add a regional dip or a convergence instead of subtracting it as was done in Figure 1, the method is exactly the

same except that the contours run in the opposite direction diagonally across the parallelograms formed by the intersections of the map contours and the grid lines.

In a region where the subsurface structure is more pronounced than that at the surface, elimination of the regional dip gives a picture which is surprisingly similar to the subsurface structure. It also reveals the true nature of the structure much better than does a map containing the regional dip. For example, the typical noses and terraces of the Mid-Continent region become easily recognizable as domes, low anticlines, or fault blocks when the regional dip has been removed.

JOHN L. RICH

UNIVERSITY OF CINCINNATI
July 16, 1935

FAULT-BLOCK NATURE OF KANSAS STRUCTURES SUGGESTED BY ELIMINATION OF REGIONAL DIP

In the preceding geological note, "Graphical Method for Eliminating Regional Dip," a simple graphical method for eliminating regional dip from a contour map was described. When the method is applied to typical structure maps of eastern Kansas a striking rectangular structural pattern strongly suggesting a mosaic of fault blocks is revealed in many places.

Many structures, as actually mapped, do not suggest such a pattern, but they reveal it clearly after the regional dip is eliminated. The writer has noticed this on many of his large-scale detailed maps contoured with an interval of 2 feet, but it is clearly shown also on maps of smaller scale and 10-foot interval (Fig. 1 and Fig. 2).

Figure 1 is traced from a map of an area in western Greenwood and eastern Chase counties, Kansas, compiled by Russell S. McFarland and published in the *Oil and Gas Journal* for October 22, 1925. It is typical of the structure of much of the eastern part of the state.

Figure 2 is the same map after the elimination of a regional dip of 26 feet per mile N. 70° W. On examining this map, one is at once struck by the pronounced angular pattern of the structure and notes that the area seems to be divided into blocks bounded by nearly straight sides, or fracture lines, one set extending approximately northeast and southwest and the other about N. 30° W.

A structure like that extending northeastward from the southwest corner of Figure 1 appears like a low fold on Figure 1, but after

the regional dip is removed (Fig. 2), it becomes evident that the feature is a straight boundary between two blocks, one dropped down considerably with respect to the other.

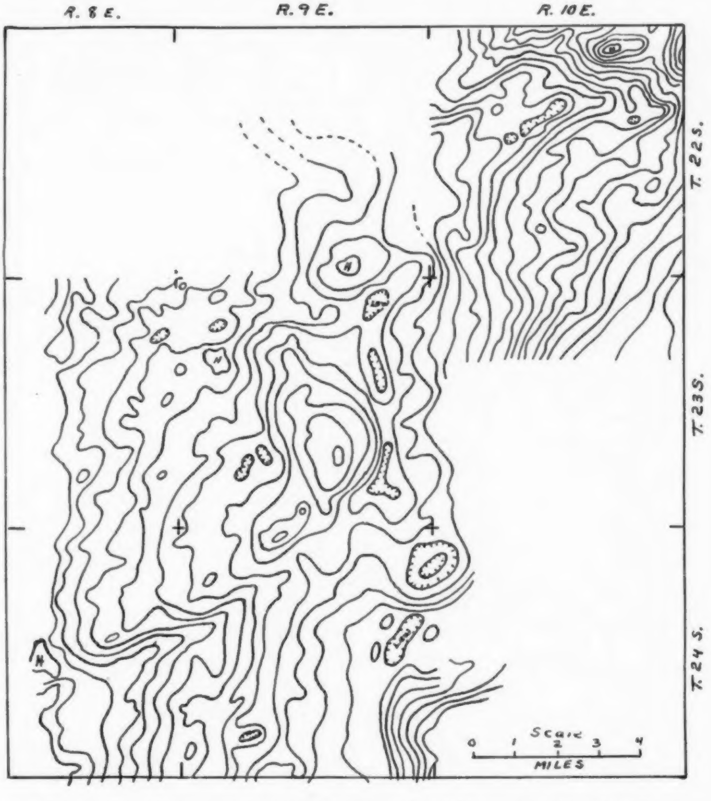

FIG. 1.—Structure map of part of Greenwood and Chase counties, Kansas. Contour interval, 10 feet. Regional dip about N. 70° W. Traced from map by Russell S. McFarland, *Oil and Gas Journal* (October 22, 1925), p. 72.

Pronounced lineaments bounding such blocks recognizable in Figure 2 are shown in Figure 3 representing the same area drawn to the same scale, but reduced slightly more.

It is to be noted that in addition to the pronounced angular blocks just described, the structural map shows the ordinary structural domes and hollows without definite trend or alignment. It is interest-

ing to note that on at least one of the larger of these domes—that in the northeastern part of T. 22° S., R. 10° E.—drilling has revealed a definite thinning of the Pennsylvanian section, indicating that the feature was present and perhaps growing during Pennsylvanian sedi-

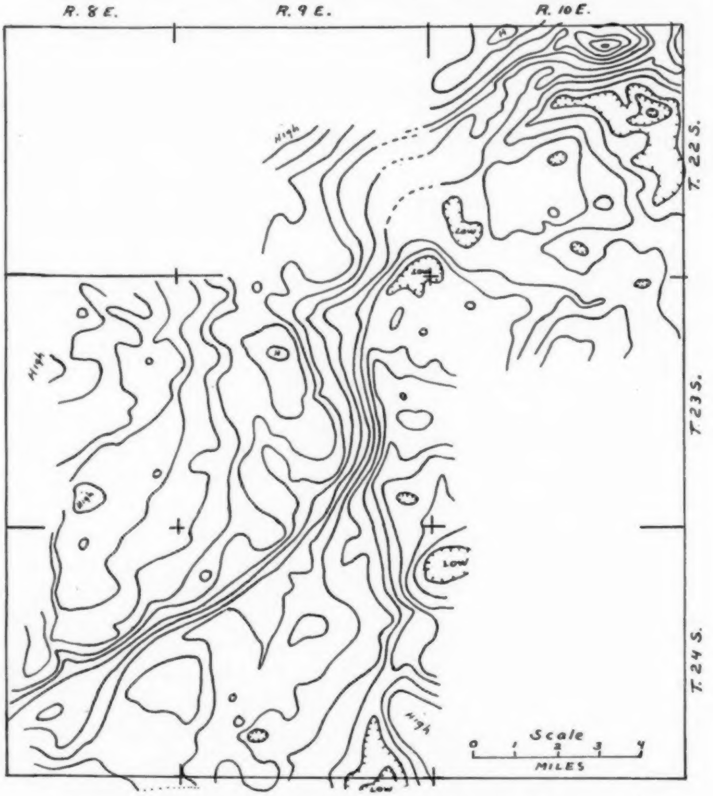

FIG. 2.—Same map as Figure 1 after elimination of regional dip of 26 feet per mile N. 70° W. Note angular boundaries of blocks.

mentation, whereas one of the linear deformations—that in the northwestern part of the same township—shows no change in thickness in the Pennsylvanian section, indicating that the deformation occurred after Pennsylvanian sedimentation had been completed.

The pattern of angular blocks revealed when the regional dip is removed strongly suggests that a mosaic of blocks has been jostled

up and down along two systems of fractures nearly at right angles to each other. It is suggested that they represent readjustments in a

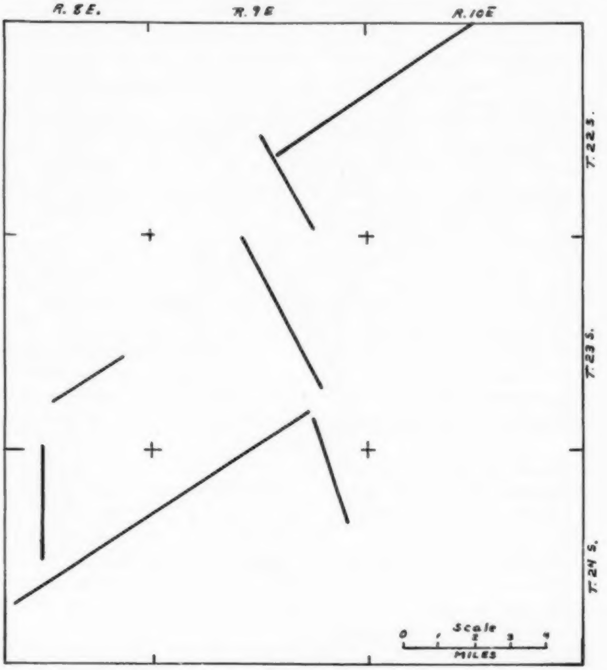

FIG. 3.—Most pronounced fracture lines or lineaments of Figure 2.

fractured pre-Cambrian basement expressed in the sedimentary cover by corresponding monoclinal flexures. The information already mentioned suggests a post-Pennsylvanian date for these readjustments.

JOHN L. RICH

UNIVERSITY OF CINCINNATI
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DISCUSSION

AGE OF BISSETT CONGLOMERATE

The recent thoughtful and informative paper by J. E. Adams in the July *Bulletin*, pages 1010–22, "Upper Permian Stratigraphy of West Texas Permian Basin," is an interesting contribution to this difficult subject. Limitations of space prevent comment on its many commendable features, and this note must be devoted to an attempt at clarifying one of the debatable points mentioned, namely, the age of the Bissett conglomerate.

On page 1022 is the statement: "The Bissett formation of the Glass Mountains, which has been regarded as uppermost Permian, appears to be early Cretaceous on the basis of fossils and stratigraphic continuity." To one who has participated in a growth of ideas on this formation, from a time when its age was suggested only by inference, to the time when its age assignment is based on a considerable body of concrete fact, this brief statement is disappointing. It does not take into account either a contrary expression of opinion by a number of geologists, or several lines of physical and fossil evidence.

The Bissett conglomerate crops out along the northwest foothills of the Glass Mountains, being underlain by dolomitic marine formations of Permian age, and overlain by sandstones and limestones of the Comanche series, or Lower Cretaceous. Southeast of the Bissett exposures the Cretaceous rests on the upturned edges of various Permian and pre-Permian rocks. The Bissett is composed of water-worn fragments derived from the erosion of the older rocks, and is largely, if not entirely, of non-marine origin. Most of its exposures are therefore unfossiliferous.

Evidence has been presented elsewhere in detail to show that the Bissett is separated by an important unconformity from the Cretaceous,[1] and that this plane of unconformity is the same as that which separates the Cretaceous from the underlying rocks elsewhere in the same region. Thus, at many places the difference in dip between the two units is well marked. Moreover, where separate members may be distinguished in the Bissett (as on the hills 2 to 4 miles north of the mouth of Gilliland Canyon), the Cretaceous strata are found to lie on different beds at near-by points. The lowest beds of undoubted Cretaceous age may be traced for long distances, which implies much more uniform conditions of deposition than those during Bissett time, and they lie indiscriminately on both the Bissett formation and the older rocks. If the unconformity between the known Cretaceous and the Bissett is of the importance suggested by the field relations, the two can hardly be a part of the same geologic system.

Even more convincing than this evidence, which is, of course, in part deductive, is that furnished by the fossils. Fossils are not common in the formation, but one locality, near the lower end of Hess Canyon, has furnished

[1] P. B. King, "Geology of the Glass Mountains, Pt. 1," *Texas Univ. Bur. Econ. Geol. Bull. 3038* (1931), p. 87. Also under the local descriptions on the two preceding pages.

invertebrates, vertebrates, and plants to several collectors, including E. H. Sellards, Sidney Powers, and myself. Sellards has made several visits to the spot, and has obtained the largest amount of material. The fossiliferous bed lies not far down the slope from undoubted Cretaceous beds and, of still more significance, overlies 650 feet of conglomerates of typical Bissett character. Information on the fossils has been printed several times in publications accessible to all geologists.[2]

The vertebrate bone, which was studied by E. C. Case, was assigned by him to a Triassic age. In a recent conversation Dr. Case confirmed this interpretation, and stated that it definitely could not be either Cretaceous or Permian. The plant remains were studied by David White, and were tentatively assigned to the Permian, although many elements of Mesozoic aspect were recognized. The writer has since been informed by C. B. Read, of the United States Geological Survey, who has also studied the flora, that the later collections of Sellards tend to strengthen a Triassic age assignment, and weaken a Permian age assignment. Thus, the form which was originally identified as *Cordaites* (an undoubted Paleozoic genus) is seen in the light of further material to belong more probably to a related Triassic genus. According to Read:

> The genera are *Pelourdea* (was called *Cordaites*), *Zamites*, *Brachyphyllum*, *Voltzia*, and several fern fragments of obvious Mesozoic types. I prefer to make no more than generic assignments at this time, due to the fact that most of the species are new. The plants are all early Mesozoic types, although some of them have been noted in the literature as occurring sporadically in the Permian. However, in such cases they are associated with clear Permian types, and there are no elements of any Permian flora in the Bissett collections. Furthermore, the cycad (*Zamites*) is particularly Mesozoic in its appearance. I feel that the Permian possibility can be definitely ruled out.
>
> Furthermore, from what I have seen of the Dockum flora at localities farther north, it is quite unlike that of the Bissett and certainly younger. In fact, the flora of the Bissett reminds me very much of a flora of Middle Triassic age described by Wills several years ago from a locality in England.

Read's recent conclusions would seem to bring the plant and vertebrate evidence into close agreement, and the writer is now inclined to support Lang's suggestion that the Bissett is of pre-Dockum Triassic age.[3]

The evidence on which Adams' conclusion is based is not known to me, but I can suggest certain possibilities. So far as I know, no beds similar to the Bissett have been encountered by drilling north of the Glass Mountains, but its appropriate stratigraphic position is occupied by sandy and shaly beds which contain few fossils other than *Chara* fruits. These are regarded as of early Cretaceous, and perhaps of Glen Rose age.[4] Their extension southward toward the Glass Mountains is not certainly known. As suggested in the Glass Mountains bulletin,[5] outlying exposures northwest of the main Bissett

[2] E. H. Sellards, in "The Geology of Texas, Vol. 1," *Texas Univ. Bur. Econ. Geol. Bull. 3232* (1933), p. 155.

P. B. King, "Permian Stratigraphy of Trans-Pecos Texas," *Bull. Geol. Soc. America*, Vol. 45 (1934), pp. 738–39.

[3] W. B. Lang, "Upper Permian Formations of Delaware Basin of Texas and New Mexico," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 19 (1935), pp. 269–70.

[4] W. S. Adkins, "Geology of Fort Stockton Quadrangle," *Texas Univ. Bur. Econ. Geol. Bull. 2738* (1935), pp. 33–37.

[5] P. B. King, *op. cit.*, p. 87.

area, and represented as Bissett on the accompanying geologic map, may instead be equivalent to the *Chara*-bearing early Cretaceous. The absence of Bissett conglomerate at the north, and of *Chara*-bearing beds at the south would suggest that they were equivalent, were there not evidence to the contrary. It is worth noting also that the outlying exposures mapped as Bissett would be the natural point of departure in carrying any subsurface correlations northward, rather than the more typical exposures farther back toward the mountains.

In summary, the physical, and especially the fossil, evidence strongly indicates that the Bissett conglomerate is much older than the Cretaceous. The present evidence favors an early Triassic age, rather than the Permian age which was first suggested for it. Certain outlying exposures, however, originally mapped as Bissett, may in fact be younger. This may be a partial cause for the suggestion that the formation is of Cretaceous age. It would seem that the Bissett has no recognizable counterpart in the Permian basin area on the north, and it may be that the formation is preserved only as a relatively narrow, wedge-shaped mass along the northwest side of the Glass Mountains, whence most of its sediments came.

PHILIP B. KING

UNITED STATES GEOLOGICAL SURVEY
WASHINGTON, D.C.
August 10, 1935

AGE OF DEVONIAN OF SOUTHWESTERN PENNSYLVANIA

In the June, 1935, issue of this *Bulletin*, pages 912–915, Caster, Torrey, and Chadwick have admirably presented the case of the "Bradfordian series" of northwestern Pennsylvania. In his part of the discussion Dr. Caster has wandered far from that area and taken exception to Willard's determination of the age of the late Devonian exposed on Chestnut Ridge in southwestern Pennsylvania.[1] Willard correlated this with the lower Chemung of New York, basing his belief partly on the fossils and partly on the physical evidence, for there is a definite stratigraphic break between the highest Devonian beds and the base of the so-called "Pocono" of the region. Recently, personal communications from several geologists interested and further studies by the Pennsylvania Survey in this region have tended to confirm Willard's opinion as to the importance of this break. Although Dr. Caster has admittedly paid little attention to the region, it is not improbable that his collection contains material which Willard has not found. Nevertheless, Caster's determination of the age based on the material he reports is not convincing. *Pararca* and *Ptychopteria* he identifies, *without specific determination*, associated with a variety of *Spirifer disjunctus* with fine ribs resembling *Spirifer mesastrialis*. This association he claims places the beds in the Conewango. Certainly these fossils even as so associated can hardly prove the age of the beds as against the lists already published and the physical evidence cited. *Pararca* has been found to range at least from the Onondaga through the Chemung. *Ptychopteria* is reported from the Helderberg in New Jersey, the Woodmont (Ithaca) in Maryland, and abundantly, it seems, from the Panama conglomerate in New York. In the collections of the Pennsylvania Topographic and Geologic

[1] Bradford Willard, "Chemung of Southwestern Pennsylvania," *Proc. Pennsylvania Acad. Sci.*, Vol. 7 (1933), pp. 148–59.

Survey are specimens from the Harrell shale and Trimmers Rock sandstone, both of Portage age. Possibly these forms are confined to younger beds in the north, but their range toward the south is fairly inclusive. The variation of *Spirifer disjunctus* is fairly common in the lower Chemung of south-central Pennsylvania. Finally, the age determination of the Devonian is receiving further corroboration from the plants. A letter from Mr. William C. Darrah of July 1, 1935, to Willard discusses the flora from the highest Devonian of the near-by and closely related section at Ohiopyle. Darrah reports that the plants he collected there show "absolutely no Mississippian tendencies and probably indicate that the rocks there are not the youngest Devonian." Incidentally, Dr. Caster cites Mr. Chadwick's recent remarks upon the Chestnut Ridge Devonian as corroboration. So far as the writer can determine, Mr. Chadwick had not seen the area when he wrote, and merely based his conclusions on published, more or less incorrect, data. It is regrettable that Dr. Caster should take exception to Mr. Chadwick's use of published and unchecked lists of fossils from New York, and yet accept his untried statements for southwestern Pennsylvania. Possibly the author is wrong in his correlation of the Chestnut Ridge Devonian with the lower Chemung, but in self-defense, these remarks are offered with the plea that those who would find errors in published accounts first make a thorough study of the field conditions before going to press.

BRADFORD WILLARD

PENNSYLVANIA TOPOGRAPHIC AND GEOLOGIC SURVEY
HARRISBURG, PENNSYLVANIA
July 19, 1935

Dr. Willard has ably summarized our difference of opinion as to the age of strata exposed in contact with the "Pocono" sandstone in one specific place on the Chestnut Ridge anticlinal inlier. This occurrence is important in determining the extent of the Conewango or other series of the Upper Devonian in western Pennsylvania, and through previous mention in the problem[2] seemed germane to a discussion of the Conewango relations in western Pennsylvania. The writer has twice visited and collected from the faunule in question under circumstances which are outlined in the following letter which he wrote to Dr. Willard on January 21, 1935.

> In reply to your inquiry about the Devonian fossils which I collected on the Chestnut Ridge anticline I would say: Last Spring during the Pennsylvania Geological Field Conference at Pittsburgh and again a few weeks later I collected some fossils along the Old National Pike, or Route 40 as it is now called, at a place approximately half way between Hopwood and the Summit Hotel, near milepost 59. This is a short distance up the flank of the anticline not far above the roadhouse which goes by the name of "The Turkey's Nest." The Devonian exposure shows also a minor overturned fold in addition to many fossils. The upper part of the exposure shows the contact between fossiliferous shales and a barren sandstone which I was given to understand is considered as the base of the "Pocono." In the shales of the Devonian member, which I was given to understand had been determined on the basis of the fossil fauna as lower Chemung, I was fortunate enough to discover several specimens of the very characteristic Conewango forms, *Pararca* sp., *Ptychopteria* sp., and a very distinct mutant of *Spirifer disjunctus*. These fossils, in which I have grown [accustomed] to place considerable trust, seem to warrant considering the Chestnut Ridge strata at the place indicated as Conewango in age. Possibly they are correlates of the Oswayo beds in McKean County. The fossils came from the upper 20 feet or so of the exposure, and range from 6 inches of the contact with the "Pocono" to near the fold disturbance. I understood that these

[2] C. Butts, *Pennsylvania Top. and Geol. Survey Rept. 1906–08* (1908), p. 198.

fossiliferous beds were the only ones known to date on that portion of the anticline. Certainly there is no tremenduous disconformity in the southwestern corner of the state which cuts out all the Devonian strata above the lower Chemung. It would seem that the Devonian history of that [specific] area was essentially the same as that of northwestern Pennsylvania.

More specific details of the fossils of Conewango stamp were desired by Dr. Willard in his letter of January 22, 1935, in which he wrote in part as follows.

. . . I was open to conviction, and if your discovery actually places the Devonian beds considerably higher than I had at first supposed them to be, it ties in satisfactorily with the observations made by Hitchcock and me at Ohiopyle. These observations, you understand, were made after my paper on the southwestern region was published. I should like to know the specific designations of the pelecypods you found. There seems no doubt that your material came from what we have been calling the top of the Devonian.

In my letter of reply (January 24, 1935), it was explained to Dr. Willard that

The pelecypods which I found at the locality under current discussion were: *Pararca* cf. *venusta* Hall, *Ptychopteria* sp. undet., and *Pararca* sp. nov. . . . The form which I noted closest to *venusta* Hall is somewhat smaller than the normal specimens of that species. The second *Pararca* was very similar to forms which I have collected from the Kushequa shale of Knapp age on Kinzua Creek. However, when I locate the material again I dare say that the likeness will be less striking than it seems in memory. At any rate the second *Pararca* is undescribed. The striae are fine and the size average for *Pararca*, if that means much. The *Ptychopteria* was definitely *Ptychopteria* and not the more ubiquitous *Oleanella*. The species of *Ptychopteria* was not determined, and the material is buried at present. The form it most closely resembled is the common large *P. beecheri* of the Allegany River area of Venango and Warren Counties (Middle Conewango into the Knapp suite only). Sorry that the list can't be more specifically imposing than it is, but for the correlation in broad terms the generic identification is adequate anyway. They are definitely Conewango in age.

In this article, Dr. Willard casts some doubt on the reliability of these genera as index fossils in citing the reported occurrence of *Ptychopteria* from the Helderbergian through the Conewangan, and that of *Pararca* from the Onondagan through the Conewangan. He might have added wide geographic range "from Russia to Colorado" and still have been within the *published* record for the genus *Ptychopteria*. A distinction must be made, however, between the actual occurrence and the *reported* occurrence in faunal lists and in certain reports where there is apparent misidentification.[3] The genus *Ptychopteria* was originally more inclusive than now seems tenable. *Oleanella* Caster embraces several species of Conewango and sub-Conewango pelecypods which were formerly included in *Ptychopteria*. Distorted actinopteroids not infrequently resemble this genus as well. It is known to the writer that an incomplete *Panenka* has been identified from the Ithaca as *Pararca*.

[3] The writer has recently examined the fossil material from the Trimmers Rock sandstone and Harrell shale in the collections of the Pennsylvania Topographic and Geologic Survey in Harrisburg and finds that the fossils assigned to the genera *Pararca* or *Ptychopteria* belong without exception to other genera. In this connection of sub-Conewango occurrence of these genera the following solicited statement from Mr. Charles Butts of the United States Geological Survey is offered with permission. (Communication of July 31, 1935) " . . . I know of no occurrence of either the fossils (*Pararca* or *Ptychopteria*) in any other formation than the Conewango, nor in any locality outside of western New York and Pennsylvania. If there is anything to the contrary it must be a very recent discovery for nothing of the kind has ever been reported so far as I am aware . . . ."

To our best information these genera, in the strict sense of their original designation or subsequent delimitation (from the Conewango series) occur only in that series in the Appalachian province and are presumably still trustworthy indices for the stratigrapher. An illustrated account of their discovery below the Conewango would, however, be most welcome, for the origin of both genera is an enigma today. Possibly the letter quoted will partially explain the absence of specific labels which Dr. Willard deplores. Incidentally, the Panama conglomerate is the basal member of the Venango stage in the Conewango series and is rightly characterized by both of the genera under discussion.

The variant of *Spirifer disjunctus* which superficially resembles *Spirifer mesistrialis* has been illustrated by Caster[4] and is being described (in manuscript) as *S. disjunctus* var. "*warrenensis.*" It seems to be an excellent guide to the Conewango, especially the upper part of the series, and is possibly distinct from the forms which Dr. Willard reports from the Chemung of central Pennsylvania.

To those who have collected and made some study of the Upper Devonian flora of the Plateau area, Mr. Darrah's categorical pronouncement, quoted by Dr. Willard, which is unsupported by citation or explanation, is not readily acceptable. The fossil flora which might be described as exclusively Devonian with which we are as yet familiar is circumscribed indeed, and has for the most part been imperfectly studied. Among such exclusively Devonian forms would presumably be the genera *Callixylon* and *Psilophyton.* But the commoner floral elements of the Devonian, such as the lycopods and the seed ferns, are usually viewed as precocious Mississippian or Pennsylvanian plants and it would be unwise to stamp them as devoid of all Mississippian tendencies. They are the chief floral types with which the writer is familiar in the Upper Devonian. Paleobotanists, with whom the writer has discussed the matter, have deplored the inadequacy of our information on the stratigraphic range of most Upper Devonian plants and have marveled at Mr. Darrah's conclusions as cited by Dr. Willard. Mr. Darrah's observations may be utterly astute, but they raise doubts rather than credence when offered in this unsupported manner.

The faunal lists of Drs. Stevenson and Willard on which Professor Chadwick largely based his long-range correlations include an anomalous assortment of genera and species most of which have either actually or by implication not very limited range. On February 20, 1935, Dr. Willard sent the writer a "Revised faunal list from the Uppermost Devonian exposed along the National Pike, east of Uniontown, Fayette County, Pa.," in explanation of which he said in part:

> I enclose some faunal lists which may interest you, either because they confirm what you think, or disagree with your ideas. They are a result, first, of revising my identifications made some four years ago of the Uniontown material, and second, identifications of additional material since collected. . . .

This list of the Uniontown fauna comprised some thirty entries in all, eight of which were not generically determined, five forms not specifically determined, four forms referred specifically with doubt, and two forms comparatively identified. Ten fossils were specifically determined. *Stropheodonta demissa*, *Camarotoechia congregata* var. *parkheadensis*, *Spirifer mesistrialis*,

[4] *Bull. Amer. Paleont.*, Vol. 15 (1930), Pl. 23, Fig. 3.

and *Glossites lingualis*, which were reported without qualification, are typically Portage and Chemung elements which may in part range into the Canadaway; the last but one may be the aforementioned *Spirifer disjunctus* var. "*warrenensis*." The occurrence of *Camarotoechia horsfordi*, which is typically of the Senecan series, is difficult to understand, as is also the questioned identification of *Reticularia praematura* in such an assemblage, for the latter was described from and supposedly does not extend below the Conewango. This form would lend considerable support to the occurrence and significance of *Pararca* and *Ptychopteria*, which do not appear in Dr. Willard's lists. A cephalopod which he compared with the "*Orthoceras*" (*Spiroceras*) *crotalum* of the Middle and Lower Upper Devonian possibly is congeneric with the genus *Neocycloceras* of Flower and Caster[5] the known species of which are Conewango exclusively.

It might not be inappropriate to stress once more the danger which lies in the whole-hearted acceptance of unsupplemented faunal lists and to urge fuller paleontologic publication with adequate illustration. All of the students who have worked on the stratigraphy of the Upper Devonian have on occasion placed too much faith in the labelled or printed fauna, to their temporary stratigraphic error. In our various faunal-list opinions on southwestern Pennsylvania it should be mentioned in passing, out of fairness to Professor Chadwick should Dr. Willard be proven correct in his faunal and stratigraphic conclusions, that these two gentlemen are in closer accord than are Professor Chadwick and I. Contrast the proximity of the Cayuta monothem of the Chemung stage to the Canadaway stage of the Chautauquan series with the remoteness vertically of the Canadaway stage from the superior Conewango series. Dr. Willard's excellent work needs no defense and undoubtedly when more field work has been carried out by all of the Devonian students involved in this difference of opinion, the truth will out and harmony will result.

KENNETH E. CASTER

PALEONTOLOGICAL RESEARCH INSTITUTION
ITHACA, NEW YORK
July 30, 1935

In Dr. Caster's supplementary discussion he has cited additional evidence to uphold his contentions as to the age of the Devonian of southwestern Pennsylvania. Had these data been given by him originally, his point would have been far stronger. Admitting that certain pelecypods he cites now have, according to his interpretation, a much more restricted range than is generally supposed, there are still unexplained anomalies in the fauna. A disconformity certainly exists between what are called Devonian and Mississippian strata in southwestern Pennsylvania. Its magnitude may eventually turn out to be considerably less than was at first supposed by Willard. Nevertheless, too little is known now to admit of our making a final decision. Even when such a decision may have been reached and agreed to by all of us, there still remains the question of the age of the succeeding "Pocono." Possibly in that will be found the key to the explanation of the hiatus.

BRADFORD WILLARD

PENNSYLVANIA TOPOGRAPHIC AND GEOLOGIC SURVEY
HARRISBURG, PENNSYLVANIA
August 23, 1935

[5] *Bull. Amer. Paleont.* Vol. 22 No. 75 (August 23, 1935), p. 210.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 19, NO. 10 (OCTOBER, 1935), PP. 1551-1566

REVIEWS AND NEW PUBLICATIONS

* Subjects indicated by asterisk are in the Association library and available to members and associates. A list of technical periodicals available for loan to members and associates was published in the *Bulletin*, Vol. 18, No. 9 (September, 1934), pp. 1215–17.

"First Order Triangulation in Texas (1927 Datum)." By HUGH C. MITCHELL. *U. S. Coast and Geodetic Survey Spec. Pub. 189* (1935). 431 pp., 48 figs., mostly sketch maps. For sale by Supt. Public Documents, Washington, D. C. Price, $0.50.

This publication gives the detailed data for the net of first order arcs of triangulation with which the United States Coast and Geodetic Survey has covered the state of Texas. The arcs are more or less as follows: north and south across the state along the 94th and 98th meridians and from Amarillo south along the 102nd meridian, east-west across the state more or less along the 32nd parallel, along the Gulf Coast from Brownsville to El Paso, from Wichita along the Texas-Oklahoma border to the New Mexico line, east-west across the Panhandle through Amarillo, and from San Antonio to Del Rio. This triangulation of course provides the framework on which all spacially accurate maps of Texas must be based.

The book gives: detailed descriptions of the triangulation stations, the latitude and longitude of the stations to thousandths of a second, the distance between stations at sea-level, the elevation of many stations, the latitude, longitude, and elevation of many objects such as water towers, church spires, windmills conspicuous from the triangulation stations.

The present book supersedes Appendix 6 Report for 1901, Appendix 4 Report for 1903, Appendix 5 Report for 1905, Appendix 5 Report for 1911, Special Publications 11, 54, and 88, but not 17.

DONALD C. BARTON

HOUSTON, TEXAS
July 10, 1935

**Erdöl-Muttersubstanz* (Mother Material of Petroleum). Edited by OTTO STUTZER. *Schriften aus dem Gebiet der Brennstoff-Geologie*, Heft 10 (1935). 181 pp. Price, RM. 17.

This publication is a collection of seven papers relating to source beds.

1. E. Wasmund, "Die Bildung von anabituminösem Leichenwachs unter Wasser" (The Subaqueous Formation of Adipocere-Like Substances That May Serve as Source Material of Oil), pp. 1–70.
2. K. Krejci-Graf, "Zur Bildung bituminöser Sedimente" (The Formation of Bituminous Sediments), pp. 71–94.
3. F. Hecht, "Grundzüge der chemischen Fossilisation" (Principles of Chemical Fossilization), pp. 95–120.
4. A. Treibs, "Pflanzensubstanz als Muttersubstanz des Erdöls" (Vegetal Matter as Source Material), pp. 121–48.

5. R. Potonié and D. Reunert, "Geologisch-chemische Untersuchungen von Sapropelen des Unterückersees und Sakrower Sees" (Geochemical Studies of Organic Sediments in Lower Ücker and Sakrow Lakes), pp. 149–69.

6. H. Steinbrecher, "Das Fehlen höherer Temperaturen bei der Entstehung des Erdöls unserer Erdöllagerstätten" (The Lack of High Temperature in the Formation of Oil), pp. 170–74.

7. D. Wolansky, "Beiträge zur Frage der Erdölmuttersubstanz und ihre Umwandlung nach Untersuchungen russischer Geologen" (Comments on the Question of Source Beds as Indicated by Work of Russian Geologists), pp. 175–81.

Wasmund endeavors to show that subaqueous alterations of organic matter, particularly of fats and proteins, lead to the formation of calcium soaps, which may serve as source material of oil. In support of this concept he assembles data on the formation of adipocere from numerous types of vertebrate animals, including man, that have been submerged in water or ice for a number of years. The data he presents seem to indicate that in the process of formation of such adipocere-like material, the fats tend to become more saturated and to combine with calcium in the form of soaps. In fact, throughout the paper he implies that adipocere is synonymous with calcium soap. The author believes that some of the fatty material of the adipocere is derived from proteins by the action of anaerobic bacteria and the data he presents, though not conclusive, certainly are suggestive.

The author was not able to find evidence one way or the other that adipocere could form from the invertebrate or lower organisms, which are the source of most of the organic constituents of sediments, but he presumes that by analogy with the higher types of life, the lower forms under proper conditions should lead to the formation of insoluble soaps. At the close of the article, the statement is made that it would be desirable to analyze sediments to see how much insoluble soap is present, but no quantitative data on the soap content of sediments are given.

In commenting on this paper the reviewer would like to mention that the presence or absence of insoluble soaps in sediments is very pertinent to the problem of source beds and should be investigated in detail. The insoluble soaps, however, are recovered from sediments with difficulty and almost nothing is known as to the quantity of such soaps present. However, even if it should be demonstrated that they occurred in significant quantities, it does not necessarily follow that they would be good source materials, because it is possible that they may be so stable that they will persist throughout geologic time.

Krejci-Graf has written more about the origin of oil than any other European geologist. The refreshing thing about his writings is that he alters his concepts as additional information is brought to light. The paper in this volume is only a summary of his ideas. For more detailed accounts, the reader should consult his articles in the *Neues Jahrbuch* for 1934, Beilage Band 73, pp. 165–210, or in the *Geologische Rundschau*, Band 26 (1935), pp. 1–65. Krejci-Graf adheres to the complicated terminology of bituminous products in vogue among German authors. "Protobitumen" represents the organic constituents that become deposited in recent sediments. "Anabitumen" indicates these constituents after they have been worked over by bacteria and other diagenetic processes for a while. "Polybitumen" represents a later

stage in which a part of the organic matter has been polymerized. Krejci-Graf uses the term, however, in the sense of solid organic matter that has been adsorbed by clay particles. Polybitumen upon further change goes to "Katabitumen," which represents solid products, or to "Ekgonobitumen," which refers to liquid hydrocarbons that constitute ancestral petroleum.

These various substances, however, have not been isolated and they are somewhat theoretical in nature. Krejci-Graf, for instance, maintains that liquid hydrocarbons when first formed are adsorbed by clay particles and that no petroleum can ever migrate out of a shale until an excess of oil over that which is adsorbed is produced. Consequently he believes that source beds must be very rich in organic matter. In support of his contention he cites the Roumanian fields, where the sole possible source, according to his interpretation, is the Cornu shale, which is extremely rich in organic matter. He also holds that the only deposits forming today which belong to the category of future source beds are the sediments of the Black Sea which, according to Archangelsky, contain from 23 to 35 per cent organic matter. However, in many fields in the western part of the United States, for many hundred feet above and below the oil zones, and also in the oil zones, the sediments contain very little organic matter. Only 4 per cent of the several thousand samples of ancient sediments the reviewer and his co-workers have studied contain more than 5 per cent organic matter. Accordingly, the organic content of the sediments at time of deposition likewise was low, unless the organic constituents were largely destroyed while the sediments were buried, which, as pointed out in the reviewer's paper in the *Oil and Gas Journal* in November, 1934, seems improbable. Richness in organic content probably is a favorable characteristic of a source bed, but according to the data presented above, it would seem as if extreme richness were not an essential requisite.

Krejci-Graf, along with nearly everybody else, believes that organic matter is preserved in sediments only in a reducing environment in which oxygen is excluded and hydrogen sulphide is present. Reducing conditions of course will favor the preservation of organic matter, but they are by no means essential, as practically every one of the 2,000 recent and 5,000 ancient sediments considered in the review contain at least a measurable trace of organic matter, and more than half of them contain at least 1.5 per cent organic matter. The water that overlay most of the recent sediments which were examined was not devoid of oxygen and it is hard to conceive that all the ancient sediments were deposited in water that contained no oxygen. It is evident, therefore, that absence of oxygen in the overlying water is not essential for the preservation of organic matter in the sediments, but it is of course possible that the particular substances that generate petroleum are laid down in an environment deficient in oxygen.

Hecht's paper is mainly a summary of his article on the decomposition of various types of meat and fish when submerged in water or buried in sediment, published in *Senkenbergiana*, Vol. 15 (1933), pp. 165–249. He found that the proteins of the higher organisms decomposed almost completely and accordingly concluded that the proteins of the lower organisms that form the main source of the organic constituents of sediments, likewise should decompose almost totally before being deposited in sediments. The appreciable nitrogen content that is found in sediments, however, indicates that some of the nitrogenous compounds are not destroyed completely. Hecht

postulates that these resistant substances which escape decomposition, especially faecal matter of bottom organisms, constitute a main source of petroleum.

Hecht attacks Wasmund's concept of calcium soap formation, mainly for the reason that he (Hecht) failed to extract saturated calcium soaps from a piece of shark that had been buried in sediments for a period of years, though he was able to recover a considerable amount of unsaturated fatty material that was not in the form of soap. He also devotes considerable space to attacking the reviewer's procedure of estimating organic content of recent sediments from the nitrogen content. He cites several reasons why there should be no definite relation between carbon and nitrogen in recent sediments, but he does not discuss the fact that other writers—notably Archangelsky, Gripenberg, Juday, Jensen, Kuenen, Potonié, and Waksman—do find ratios similar to those observed by the reviewer.

Treib's paper is a review of Hackford's theory of origin of oil from algae, of Berl's theory of origin from cellulose, and also of his own idea that pigments, such as porphyrin, which are derived from chlorophyl and blood, may be associated with the generation of petroleum. Treib, in support of this concept, lists a great variety of crude oils and bituminous sediments in which porphyrin has been found. The presence of porphyrin in a practically unchanged form under different conditions demonstrates its chemical stability during long periods of time.

The paper by Potonié and Reunert is a summary of their chemical studies of rich organic sediments in two German lakes. This paper is a distinct contribution, as it is essentially a presentation of data rather than theories. The authors advocate the study of small areas in detail rather than general studies of large areas. They recognize that oil is formed mainly under marine conditions, but they believe that better progress can be made if lakes, which are more convenient for investigation than the sea, are investigated first. In this way the methods of study would be developed more readily, and something about the general laws of sedimentation and decomposition of organic matter would be learned. Then subsequently more costly investigations of marine conditions could be profitably undertaken.

The paper contains too much detail to be summarized here, but among the things discussed are the changes with depth of burial in the sediments of Lake Sakrow. The changes, though consistent in the two localities reported, in general are small. The hydrogen-ion concentration, organic content, carbon content, and the ratios of carbon to nitrogen and of organic matter to carbon decrease with depth of burial; and the nitrogen and ammonia contents increase with depth. The average ratio of organic matter to carbon in the sediments is 1.83, which accords with the figure of 1.82 obtained by the reviewer in the course of work that has just been completed.

Steinbrecher's paper is essentially a summary of Brooks' article in the *Journal of Petroleum Technologists*, Vol. 20 (1934), pp. 177–205, in which it is shown that the presence in petroleum of heat-unstable compounds indicates that oil must form at a temperature well below 200°C.

Miss Wolansky's article is a summary of the recent papers of the Russian geologists, Archangelsky, Kalitsky, and Orlov. Archangelsky believes sediments of the Black Sea type are common sources of oil. The organic content of ancient shaly sediments suspected of being source beds ranges from 2 to 17 per cent. Ancient sandstones contain little organic matter; the quantities

that were found range from 0.1 to 0.4 per cent. The nitrogen content of the organic constituents first increases with respect to carbon and then decreases. This inference is based on the observation that the carbon-nitrogen ratio of recent sediments is greater than the ratios both for ancient sediments and for the plankton which supplied the organic matter.

Kalitsky regards *Zostera* (eel grass) and allied plants as the main source of oil. *Zostera*, as Jensen and Petersen indicate in their publications in the Danish Biological Survey reports for 1911 and 1915, certainly may be the source of a considerable proportion of the organic constituents of brackish-water sediments, but it is doubtful whether it is a major source of organic matter in marine deposits which, as indicated by the geologic relations of the occurrence of oil, are the main sources of petroleum.

Orlov believes oil is derived largely from cellulosic constituents of marine algae. Miss Wolansky's remarks about Orlov's work are brief and it is not clear whether he distinguishes between (1) cellulosic constituents of the organic components of the sediments and (2) cellulose in the planktonic organisms in the water above.

In commenting on the origin of oil from cellulose, the reviewer would like to state that the work of the American Petroleum Institute Project on source beds seems to indicate that cellulose in sediments presumably is not a source of much oil because the quantity present commonly is less than 1 per cent of the organic content of the sediments, and only a few hundredths of one per cent of the entire sediment. However, as Brandt pointed out in 1898, in the Wissenschaftliche Meeresuntersuchungen of the Kiel Institute, the peridineans contain about 40 per cent cellulose in their bodies. The peridineans, together with the diatoms, are two of the main groups of microscopic plants in the sea that have the ability of making organic matter from inorganic constituents with the aid of sunlight. They therefore constitute a basic source of organic matter in the sea, and the organic constituents of the underlying sediments in turn are derived in part from the remains of their bodies. As they are reported to be 40 per cent cellulose (air-dried basis), one must admit that there is a possibility that a part of the organic constituents of the sediments may be derived from such cellulosic substances, but as stated above, the organic matter in sediments to only a very small degree is in the form of cellulose. That is, the cellulose seems to be largely destroyed or transformed to other compounds before it reaches the sediments. It is therefore possible that petroleum may be generated from substances derived from cellulosic constituents of the original planktonic organic matter, but whether or not it is probable that oil has such a source is a matter that awaits further proof.

PARKER D. TRASK

UNITED STATES GEOLOGICAL SURVEY
WASHINGTON, D. C.
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The Carpathian Oil Geological Institute of Poland (Warsaw), Vol. 3 (1935). In Polish. Résumé by E. FISCHER in *Moniteur du Petrole Roumain* (Bucarest, July 1 and 15, 1935). Translation of résumé. By W. P. HAYNES. Contents of original volume.

1. "Upon Diapirism," by L. Mrazec.

2. "Upon the Natural Gas Deposits of the Transylvanian Basin," by L. Mrazec.

3. "The Oil Deposits of Roumania," by G. Macovei and D. Stefanescu.

4. "Present State of Geologic Knowledge Regarding the Origin of Oil in the Roumanian Carpathians," by I. P. Voitesti.

5. "The Oil Field of Arbanasi," by R. Noth.

6 "Moreni," by A. Pustowka.

7. "Oil Deposits in the Ploesti Basin," by I. Strzetelski.

8. "Diapir Zones in the Foreland of the Polish-Roumanian Carpathians," by K. Tolwinski.

1. *Diapirism.*—The first studies upon diapir folds, later named "diapirs," were carried out by Professors L. Mrazec and H. Teisseyre in 1899–1900, although the term was first introduced in geologic literature by Professor Mrazec in 1907. He mentions all published articles upon diapirism and concludes that it occurs only in folded regions. He gives an analysis of the tectonic elements of a normal diapir: the core; the complex of strata traversed by the core which form its envelope; and the covering arch. The author agrees that the salt, due to its physical qualities, has migrated upward following the lines of least resistance toward the anticlinal form, but he maintains that it is entirely erroneous to attribute the formation of diapir cores only to salt, as has been suggested by many geologists. The conclusions are briefly as follows.

a. Diapirism is found only in folded areas.
b. Salt is commonly in diapir form in folded regions containing salt formations.
c. Diapirism presupposes a surface at depth of detachment with flowing of the separated mass toward the lines and points of least resistance.
d. The structural discord which is more or less accentuated is an essential characteristic of diapir areas.
e. All regions with salt diapirs are folded areas. In undisturbed areas where salt diapirs are present it is thought that the strata are dislocated at depth.

Diapirism is a form of folding which occurs each time that the disturbing forces act in an unequal manner, and especially more strongly at depth than upon beds near the surface.

Referring to the occurrence of crude oil in the diapir areas he says that a normal diapir opens up routes for the upward migration of oil. In Roumania the Dacic contains exploitable oil deposits only in the salt diapir zones. In areas where the Dacic is in the form of an isolated arch, not pierced by a salt core, it lacks oil deposits. Whether the crude oil of the Dacic comes from the Oligocene or Neocene it has migrated only along the discordant surfaces of the diapir under the influence of orogenic forces. Numerous typical examples are given among the Roumanian oil fields.

2. *Natural gas in Transylvania.*—The Transylvania basin consists entirely of Tertiary deposits and contains horizons with methane gas. The central portion of the basin is of Neogene deposits, but outcrops of Paleogene are found along the borders. Professor Mrazec cites the reports by Civpagea and Vancea and the geologic department of the National Society of Methane Gas upon the structure of the basin. Geologic sections by Mrazec, Jekelivs, Civpagea, and others are included.

The author states that the controversial question upon the origin of the gas, and salt waters of the gas formations, has not been satisfactorily answered. Drilling at Sarmasel appears to indicate a primary source for gas,

but another theory maintains that the exploited gas horizons are the result of degasification of a crude oil horizon at depth. In regard to the exploration necessary to find such a deep-seated oil horizon it is estimated that drilling will exceed 3,000 meters.

The reserves of gas in the producing domes of the basin are greatly in excess of the figures arrived at by Clapp in 1913. The article describes the operation of the two methane gas companies, in which the State has an 80 per cent interest.

3. *Oil deposits of Roumania.*—This article is divided into two chapters: the geology of the eastern Carpathians, and a description of the oil-bearing regions. It comprises, in part, work previously published by the writer and others in the Guide to the Excursions of the 2nd Reunion of the Carpathian Association of Roumania in 1927, and also in the report of the 1st International Drilling Congress held at Bucharest in 1925. The first chapter gives a somewhat detailed description of the three principal longitudinal zones which form the Eastern Carpathians in Roumania. These are successively from interior toward exterior: (1) the Crystalline Mesozoic zone; (2) the Flysch zone; and (3) the Neogene zone.

A geologic map of the Eastern Carpathians from the Geologic Institute of Roumania illustrates this chapter.

The second chapter gives the characteristics of the oil-bearing regions, which are as follows. 1. The Interior Flysch zone occurs in Bucovina, and in the Neamtz, Trei Scaune, Ciuc, and Brasov districts, where numerous occurrences of crude oil are known near ancient workings. 2. The Marginal Flysch zone shows outcrops which have never been explored in the districts of Falticeni and Neamtz.

The most important exploitation of oil deposits in this zone are in the Bacau district. 3. The Neogene zone of Moldavia is exploited at Campeni, Tetzcani, and Casiv. 4. In the Zone of Diapirs numerous rich oil deposits are grouped by districts. The various anticlinal zones are described and illustrated with numerous cross and longitudinal sections. The article concludes with a description of oil occurrences in the Marmuresh and southern Carpathians.

4. *Present state of geologic knowledge regarding origin of oil in Roumanian Carpathians.*—Professor Voitesti points out that although the structural knowledge regarding the oil deposits in Roumania has increased enormously since the war, due to the great number of deep wells drilled, progress in solving the problems connected with the origin of the oil has been but slight. Theories regarding the inorganic origin of oil have been abandoned for about 30 years, and the organic theory is admitted by all geologists. In recent years studies have been concerned with precise knowledge of the mother rock or of several source beds in case one admits the existence of several sources for the Roumanian oil. In order to study such a vast subject as the origin of oil one must consider the following lines of geologic deductions.

1. *Source of primary organic material.*—In Roumania Professor Mrazec has concluded that this material was furnished by animal and vegetable microorganisms, deposited in salt lakes or lagoons. Since the finding of diatoms in the Oligocene of Valenii-de-Munte, Mrazec and Macovei attribute great importance to these algae, as a primary source of organic material. An older opinion of Professor R. Zuber regards only marine algae as having furnished the primary material.

2. *Deposition of organic matter.*—The author summarizes the opinion of Professor Mrazec upon the process of bituminization, first published in 1907. According to

Mrazec, no clays, limy marls, or beds of siliceous deposits, which were deposited away from the influence of oxygen, fail to show at least some traces of hydrocarbons. The source bed for oil is formed at first of an alternating series of fine silts and porous beds—generally sand, containing the primary organic matter. These deposits are impregnated with indigenous salt water, accumulated in great quantities in marine areas. The source rock which complies with these conditions in Roumania and also may be the source for the salt deposits is the Cornu formation of Oligocene age.

Professor Macovei expressed the idea in 1931 that the Menilite shales of the marginal Oligocene and the black Barremian (Lower Cretaceous) shales of the interior Carpathian zone represent in the present formations the typical form of the source rock. The author analyzes the various opinions and describes his petrographic researches upon various possible source beds which have led him to conclude that all divisions of the stratigraphic series from Lower Cretaceous to Upper Pliocene—with the exception of Senonian, Pontien, and Levantine—contain more or less well developed source beds. He believes that the oil originates in all Cretaceous-Tertiary formations which contain suitable source beds. Displacements of the source beds permit migration and the formation of secondary deposits.

3. *Process of transformation of primary organic matter into hydrocarbons.*—The chemical process of transformation is unknown. Hypotheses are based upon laboratory experiments which can not duplicate the natural conditions. The primary organic matter under the effect of pressure and temperature, aided by the presence of alkaline solutions, was changed into petroleum hydrocarbons. According to Mrazec and Macovei, bituminization commenced with the beginning of deposition and continued gradually and increasingly during a long time. The fine grains of sand acted as catalizers in the chemical reactions, which took place at high pressures and temperatures. The hydrocarbons thus formed are related genetically to the salt waters in the sandy beds.

The author believes that the process of the bituminization of the primary organic matter is comparable to a natural distillation at increasingly higher pressures and temperatures, according to the depth of the geosynclinal zones. The first volatile products of distillation, especially H, H_2O, and CH_4, have been able to complete the chemical process by the hydrogenation of the first organic substances. He believes that the salt water only acts as a dispensing agent, aiding the solution and movement of the hydrocarbons from the source rock toward porous beds. He cites as examples the study of the anticlines of Sacel and Magura Slatioarei d'Oltenie, the anticlinal zone of Mont Lapus of Transylvania and the crystalline zone of Mont Plopis, and concludes as follows.

1. The oil is indigenous in almost all of the formations in which its characteristic manifestations occur.

2. Its origin is related, on the one hand, to the existence of organic substance—generally algal remains as primary material—finely disseminated in fine-grained marly or clayey deposits as source beds in a geosynclinal depression, and on the other hand to enormous mechanical pressures exerted upon the mother rock complex during tectonic movements. The mechanical phenomena have generated the necessary temperatures for the pressure distillation of the organic material.

3. The petroleum hydrocarbons of the different horizons should retain their initial tension equally, whether the migration of the oil is caused directly by the initial tension of the gas, or is due to tectonic forces. The oil is held under pressure by the water in the stratum and the impermeable beds covering it.

5. *Oil field of Arbanasi.*—Noth gives a brief statement on the history of this oil field. He explains the stratigraphy and tectonics of the region and describes the mud volcanoes of Beciu-Berca. The prominent anticline of

Berca, a town 19 kilometers from Buzau, is divided into two secondary anticlines, one called South Berca which has been tested without success, and one called Policiori or Arbanasi on which a good oil field has been developed. The author gives the detailed Neogene stratigraphy characterized by five stages, which are here better developed than in the sub-Carpathian region at the south. Oil production is limited to the Neotic, which is about 540 meters thick and contains 12 oil horizons in the first 400 meters. The two upper horizons either have gas or are barren near the axis of the anticline, but were productive on the flanks. The fourth horizon is now the first important producing horizon and the sixth and seventh horizons form the second producing horizon. The total production of the Arbanasi oil field, exploited by the Steaua Romana, Romana Belge de Petrole, and Unirea companies amounted to 185,420 tons to January, 1935. The average production per hectare to January, 1933, was 11,600 tons and the average production per productive well was 13,700 tons, and the average production per meter drilled was 24 tons. Numerous geologic maps and diagrams as well as photographs illustrate the article.

6. *Moreni.*—Pustowka has given a résumé of the history, geology, and Dacic and Meotic production of this area to the end of 1932. This is an important compilation of the development of the various fields along the line Moreni-Gura Ocnitei from their beginning. Geologic sections and diagrams and tables illustrate the report.

7. *Oil deposits in Ploesti basin.*—Strzetelski gives a general description of the geology and oil deposits of the Ploesti region, from the village of Mizil to the Jalomitza River. This includes the Prahova and Dambovitza districts. A geologic map, on the scale of 1:125,000, accompanies the report. The author insists that efforts be made for further exploration to discover new fields as well as deeper horizons. He believes that further geologic work in Poland in the sub-Carpathian region will discover oil deposits in relation to diapir folds. In regard to the future of the Roumanian oil industry he gives as a figure of oil reserves Garfias's figure of 67 million tons, which would last only 10 years. The reviewer regards this as too pessimistic.

8. *Diapir zones in foreland of Polish-Roumanian Carpathians.*—Tolwinski, who organized the present volume and arranged for the various Roumanian geologists to contribute articles, terminates with a study which includes the following chapters.

1. Observations on the foreland of the Polish Carpathians with certain features on the external border of the Carpathians and on the Carpatho-Podolian area.
2. Diapir zones in the foreland of the Roumanian Carpathians. He notes a dislocated zone of lower Miocene well developed between Bacau and Bazau, the diapir structure with piercing of the Pliocene by the Salifer formation in the rich oil districts of Prahova and the presence of depth of the Miocene Salifer formation with a thick cover of Pliocene in the southern portion of the Prahova area.
3. Differences and analogies in the formation and origin of diapir zones in the foreland of the Polish-Roumanian Carpathians. The author maintains that in spite of the fact that a comparative study of diapirs in the foreland area leads to the conclusion that the origin is the same in both Roumania and Poland, yet he feels there are great differences due to special geologic conditions. He analyzes the conditions in the two countries.

In Poland, the author maintains that it is necessary to carry on ample studies to define the various tectonic elements in the Carpathian region, especially the search for oil deposits at depth. These studies have been carried

on during recent years and have been accompanied by geophysical studies. A geological map of the foreland region, made by the geological service of Boryslaw, accompanies the article.

W. P. Haynes

London, England
July, 1935

Compilation of Official Geological Studies in Colombia, 1917–1933. Volume II (1935). By Otto Stutzer and Ernst A. Scheibe. Published by the Department of Mines and Petroleum, Ministry of Industries, Bogota, Colombia. In Spanish. 425 pp., 75 line drawings and photographs, 30 special plates.

This is the second volume of a compilation of scientific studies made by the geologists of the Colombian Government during the years 1917 to 1933 and is devoted in the main to the work of Otto Stutzer and E. A. Scheibe, two German geologists in the employ of the Department of Mines and Petroleum.

The volume is introduced by a map showing the location of the various areas discussed. Seventeen separate reports are printed in the collection. Of these, three are reports on railroad routes, with particular reference to construction problems; two are on glaciation in the regions about Bogota; there are two short reports on metal mines; and there are also three short reports on coal prospects. Of the remaining reports, those of interest to the students of the general geology of Colombia and to petroleum geologists in particular are as follows.

Paper No. 2. "Geological Observations During a Double Traverse of the Central Cordillera."—This is a route survey across this mountain range at the latitude of Bogota. The chapter adds little to the older German works, such as Riess and Stubbels *Riesen in Suedamerika*, and, as the mountains are composed almost entirely of metamorphosed igneous rocks and tuffs, they are of little interest to petroleum geologists. Stutzer, however, remarks

> One conclusion, though negative, is important—there are lacking in this area the Cretaceous strata whose important deposits form the principal part of the Eastern Cordillera. This determination is linked up with numerous observations of negative character in the sense that they lead to the conclusion that the Central and Western Cordilleras in their greater part appeared as dry land during Cretaceous time.

This conclusion is important if true; however, there is equally important evidence to the contrary—as follows. ?

1. No evidence of shore-line conditions have been found in the Eastern Cordillera, the Upper Cretaceous sediments there being fine shales, with little, if any, sandstone or conglomerate.

2. Within a few miles of the Central Cordillera as much as 10,000 meters of marine Cretaceous has been measured. It seems hardly probable that such a thick section accumulated within so short a distance of dry land. The safe verdict in the present state of our knowledge is the Scotch one—"not proved."

Western

Paper No. 3. "On the Geology of the ~~Eastern~~ Cordillera between Cali and Buenaventura."—This is merely a route survey of the Dagua Gorge. This Cordillera is almost wholly schist and the Cretaceous is missing. The author

"Occidental" - see original paper in Spanish.

notes the fact that the coastal plain, which is narrow, is probably of recent origin. The paper is inadequate but is the only available publication on the area.

Paper No. 4. "Notes on the Geology of Petroleum and Water in the Department of Atlantico."—This paper covers ground already familiar to American geologists through Alfred Beck's "Geology and Oil Resources of Colombia,"[1] which gives a more complete picture of the geology.

Paper No. 5. "Contribution to the Geology of the Cauca-Patia Trench."—This is also a rather limited paper but contains an exceptionally interesting series of notes by Dr. Stutzer on the rift valley of the Cauca and its structural continuation—the upper valley of the Patia. The paper is disconcerting in the way the information is scattered and in the lack of a satisfactory summary, but it remains the best paper written on this very interesting valley. It discusses the coals of the Oligocene and the occurrence of widespread deposits of diatoms due to the pounding of fresh water in the valley as a result of the faulting. No indications of oil were found and the Cretaceous and Eocene sediments which are a source of oil elsewhere in Colombia are missing.

Paper No. 6. "A Series of Brief Notes on the Regions Near Bogota."—Discusses the occurrence of gas in the lake deposits of the plateau, glaciation, the occurrence of fossiliferous Paleozoic sediments in the region of Gachala, the occurrence of the great mesas at Fusugasuga and Cunday, the valleys of Bogota and Coello, particularly with reference to the accumulation of conglomerate terraces and mesas along their courses.

Note No. 10 of the group covers the geology of a seepage on an anticline at the top of the Cretaceous section near Guataqui, and Notes Nos. 11 and 12 of this series are on the Tertiary deposits of the neighborhood of the town of Honda.

Paper No. 7. "The Geology of the Central Part of Magdalena Valley."—This paper should be read by geologists interested in the Magdalena Valley, for it discusses in some detail the stratigraphy of the area and gives tables showing the relationship of the various names used in the literature by different geologists in describing the strata and, if followed, will do much to reduce the confusion into which the nomenclature has fallen. It also covers the rather puzzling problem of the origin of the Honda formation, of possible Pliocene age. With the exception of the recent paper by Pilsbury, Olsson, and Wheeler, it is the best paper in print on this section of Colombia.[2]

The section on structure is not so illuminating. The complexities of this much-faulted valley do not lend themselves readily to short description.

In conclusion, Stutzer remarks that he differs from F. M. Anderson in believing that the Colombian oil originated in the Cretaceous and not in the Eocene. On the basis of the experience in this part of the Magdalena Valley, it is probable that Stutzer is more nearly right than Anderson, who believed that the oil originated in the Eocene.[3]

[1] *Econ. Geol.*, Vol. 16 (1921), pp. 457 *et seq.*

[2] Henry A. Pilsbury and Axel A. Olsson, "Tertiary Fresh Water Mollusks of the Magdalena Embayment," with "Tertiary Stratigraphy of the Middle Magdalena Valley," by O. C. Wheeler, *Proc. Acad. Nat. Sci. Philadelphia*, Vol. 87 (1935), pp. 7–39.

[3] *Cf.* F. M. Anderson, "Non-Marine Tertiary Deposits of Colombia," in *Bull. Geol. Soc. America*, Vol. 37 (1927).

Paper No. 8. "Contribution to the Geology of the Peninsula of Goajira."—This is the best discussion of the geology of the Peninsula of Goajira so far written. It lacks adequate maps. One interesting point brought out in the discussion is the occurrence of the great fault whose extension into Venezuela appears in the Sierra de Ocoa and which cuts off the north and northeast trending structure of the Sierra de Perija abruptly. This fault, which has not been noticed in the geological literature, is regionally one of the most important in northern South America.

Paper No. 17 is a short discussion of the oil-saturated sands at Guacheta, from which oil has been extracted by distillation and used for manufacturing asphalt for the streets of Bogota. The occurrence is of Upper Cretaceous age.

By American standards, these papers are very inadequate, but it must not be forgotten that they treat of areas upon which there is no other geological information and that these areas are peculiarly difficult for geologists to work. Many of them are at either high altitudes or in dense jungle country where little can be seen except along the tropical streams. We can be thankful for whatever information we get, and the Colombian Government is to be highly commended for making these papers generally available.

J. T. DUCE

NEW YORK, NEW YORK
August 2, 1935

Guide Book—Ninth Annual Field Conference. By the Kansas Geological Society in coöperation with the Iowa Geological Survey, State Geological Survey of Illinois, Wisconsin Geological and Natural History Survey, and Minnesota Geological Survey. Published by the Kansas Geological Society at Wichita, Kansas. 471 pp., 263 illus. 9×11.5 inches. Price, $10.00.

The Ninth Annual Field Conference of the Kansas Geological Society studied the stratigraphy and structure of the Upper Mississippi Valley and part of the Lake Superior region. The 9-day excursion extended from Iowa City, through northwestern Illinois, northeastern Iowa, western and central Wisconsin, and eastern Minnesota.

The guide book for the conference can be described with no misuse of terms as a monumental undertaking and accomplishment. Approximately 230 pages are entitled as being the log of the trip, but these pages in addition to an excellent road log contain many interpolated discussions of the stratigraphy and structure of the areas covered, of correlations between the exposures at which stops were made, and of the variations in nomenclature and interpretation of the sections since the earliest geological work in the area.

A second section (pages 237–332) is entitled, "System Papers on Geology of the Upper Mississippi Valley," and contains the following contributions.

The Mississippian System in the Upper Mississippi Valley Region, by Raymond C. Moore
Supplemental Statement on the Mississippian System in Iowa, by L. R. Landon
Stratigraphy of the Devonian System of the Upper Mississippi Valley, by Merrill A. Stainbrook
Devonian of Wisconsin, by Gilbert O. Raasch
Stratigraphy of the Silurian System of the Upper Mississippi Valley, by A. H. Sutton
Ordovician System of the Upper Mississippi Valley, by G. Marshall Kay
Mohawkian Relations in Wisconsin, by Carl A. Bays and Gilbert O. Raasch
Stratigraphy of the Cambrian System of the Upper Mississippi Valley, by Gilbert O. Raasch

The Keweenawan-Upper Cambrian Unconformity in the Upper Mississippi Valley, by Gordon I. Atwater
The Pre-Cambrian of the Lake Superior Region, the Baraboo District and Other Isolated Areas in the Upper Mississippi Valley, by Andrew Leith

A third section (pages 334–353) includes isopach maps of the post-Kinderhook Mississippian, of the Kinderhook group, and of the Devonian system by Allen C. Tester; of the Silurian system by L. E. Workman; of the Maquoketa shale by Harry S. Ladd; of the Galena, Decorah, and Platteville by John R. Ball; of the St. Peter formation by J. E. Lamar; of the Prairie du Chien group by Elliot H. Powers; and of the Trempeleau, Franconia, and Dresbach formations. The following section contains structural contour maps drawn on top of the pre-Cambrian by J. V. Howell and F. T. Thwaites, on top of the Dresbach formation by F. T. Thwaites, on top of the Jordan sandstone by A. C. Trowbridge, and on top of the St. Peter sandstone by J. V. Howell, F. T. Thwaites, and D. J. Jones.

A geologic cross section of the Upper Mississippi valley is presented in three sheets: the Wisconsin portion drawn by F. T. Thwaites, the Illinois portion by L. E. Workman, and the Missouri section by H. S. McQueen. The discussion of the cross section is by Workman.

"Miscellaneous Papers" covers the following titles.

The Geology and Development of the Wisconsin-Illinois Lead-Zinc District, by Charles H. Behre, Jr.
Cambrian Inlier at Oregon, Illinois, by Arthur Bevan
The Mississippi River Arch, by J. V. Howell
Stratigraphy of the Prairie du Chien, by Elliot H. Powers
Physiography of the Baraboo District, Wisconsin, by F. T. Thwaites
Paleozoic Strata of the Baraboo Area, by Gilbert O. Raasch
Zones of Mineralization of Underground Waters in Minnesota, Iowa, Illinois, and Wisconsin, by F. T. Thwaites
A Summary of the Stratigraphy and Structure of the Gogebic Iron Range, Michigan and Wisconsin, by Gordon I. Atwater

The volume is concluded with detailed stratigraphic sections of all exposures studied by the conference (which are also shown in generalized diagrammatic form in the "log") as well as of several exposures which could not be visited by the conference group.

In all, the *Guide Book* presents an extremely valuable summary of the present knowledge of the Upper Mississippi Valley and of the development of the views currently held on the subject. Points still in controversy are not neglected, but opposing views are set forth in what impresses the reviewer as a fair and dispassionate manner. It seems safe to say that this work will be the platform from which future geologic work in the area will advance and that it will be necessary to all students of the stratigraphy and structure not only of this region but of other areas in which correlations must be made with the Upper Mississippi Valley.

L. C. Snider

New York, New York
September 16, 1935

RECENT PUBLICATIONS

AFRICA

* "Evolution of the Congo Basin," by A. C. Veatch. *Geol. Soc. America Mem. 3* (August, 1935). 183 pp., 8 figs., 10 pls. Cloth. 6.75×10.25 inches.

AUSTRALIA

* "Australia Geology. Factors in Oil Prospecting," by D. Dale Condit. *Oil Weekly* (Houston, Texas), Vol. 78, No. 9 (August 12, 1935), pp. 38–44; 1 map. Abstracted from "Geological Factors in Oil Prospecting with Reference to Australia," by D. Dale Condit. *Australian Geographer* (Sydney), Vol. 2, No. 6 (May, 1935), 15 pp., 1 fig.

AUSTRIA

* "Die Erdölbohrungen in Österreich" (Oil Wells in Austria), *anon. Petrol. Zeit.* (Vienna), Vol. 31, No. 30 (July 24, 1935), pp. 6–7; geologic sketch map.

CHINA

* "Mesozoic Stratigraphy of Szechuan," by C. Y. Lee. *Bull. Geol. Soc. China* (9 Ping-Ma-Ssu, Peiping), Vol. 13, No. 1 (December, 1933), pp. 91–105, 1 fig., 2 pls. In English.

* "The Base of the Palaeozoic in Shansi. Metamorphism and Cycles," by P. Teilhard de Chardin. *Ibid.*, pp. 149–53, 2 figs. In English.

* "A Review of the Early Tertiary Formations of China," by C. C. Young. *Ibid.*, No. 3 (September, 1934), pp. 469–503, 17 figs., 1 pl.

* "Uralian and Permian of the Urals," by George Fredericks. *Ibid.*, No. 4 December, 1934), pp. 505–60; 2 correlation charts. In English.

GENERAL

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* "Upper Eocene Foraminifera of the Southeastern United States," by J. A. Cushman. *U. S. Geol. Survey Prof. Paper 181* (1935). 88 pp., 23 pls. Supt. Documents, Govt. Printing Office, Washington, D. C. Price, $0.25.

* "Le traitement acide et l'emploi des produits chimiques dans les sondages" (Acid Treatment and Use of Chemicals in Drilling), by W. Tiraspolsky. *Rev. Petrol.* (Paris) reprint (1935). 32 pp., 2 figs.

* "Über Veränderungen des Stickstoffgehaltes organisher Substanzen während und nach der Ablagerung" (Alteration of Nitrogenous Content of Organic Substances During and After Deposition), by Karl Krejci. *Zeit. für Prak. Geol.* (Wilhelm Knapp in Halle, Saale, Germany), Vol. 43, No. 7 (July, 1935), pp. 97–101.

* "Increasing Crude Production 20,000,000 Barrels from Established Fields" (Commercial Acidization), by John J. Grebe and Sylvia M. Stoesser, *World Petrol.* (New York), Vol. 6, No. 8 (August, 1935), pp. 473–82, 29 illus.. bibliography.

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* "Form, Drift, and Rhythm of the Continents," by W. W. Watts. *Science* (New York), Vol. 82, No. 2123 (September 6, 1935), pp. 203–13.

GEOPHYSICS

* "La méthode de prospection séismique par réflexion" (The Method of Seismic Prospecting by Reflection), by Silvain J. Pirson. *Bull. Soc. Belge des Ingenieurs et des Industriels* (Bruxelles), No. 4 (1935). 40 pp., 21 figs. 6.125 × 9.5 inches.

* "Les possibilités et les limites d'application de la geophysique" (The Possibilities and Limits of the Application of Geophysics), by W. Tiraspolsky. *Rev. Petrol.* (Paris), No. 645 (August 24, 1935), pp. 1077–78.

GERMANY

"Die Erdölfelder Deutschlands" (Oil Fields of Germany), by Walter Hantzschel. *Natur und Volk* (Frankfurt a. M.), Vol. 65 (1935), pp. 75–85, 7 figs.

"Handbuch der vergleichenden Stratigraphie Deutschlands. Zeckstein" (Handbook of Comparative Stratigraphy of Germany. Zeckstein), by E. Fulda, W. Gothan, O. Grupe, W. Haack, K. Pietzsch, L. Riedel, and E. Zimmerman II. Published by *Preuss. Geol. Landesanstalt* (Gebrüder Borntreager, Berlin, 1935). 409 pp., 100 figs., 1 map.

LOUISIANA

* "Louisiana Jackson Eocene Ostracoda," by Henry V. Howe and Jack Chambers. *Louisiana Geol. Survey Bull. 5* (New Orleans, August 1, 1935). 65 pp., 6 pls. 6×9 inches.

NEW MEXICO

* "Geology and Economic Significance of Hobbs, New Mexico, Field," by Basil B. Zavoico. *World Petrol.* (New York), Vol. 6, No. 8 (August, 1935), pp. 459–72, 10 illus.

NOVA SCOTIA

* "Lake Ainslie Map-Area (Inverness County), Nova Scotia," by G. W. H. Norman. *Canada Geol. Survey Mem. 177* (Ottawa, Canada, 1935). 103 pp., 3 figs., 4 pls., 2 colored maps in pocket. "Petroleum," p. 70. 6.5×9.75 inches. Paper. Price, $0.25.

PERU

* "Estratigrafia de Lobitos y El Alto y su relation con la microfauna local" (Stratigraphy of Lobitos and El Alto and Relation to Local Microfauna), by José Balta Hugues. *Bol. Soc. Geol. Peru* (Lima), Vol. 6, No. 3 (1934). 25 pp.

ROUMANIA

* "Les phénomènes de diapirisme et la géologie des gisements pétrolifères de Roumanie" (Diapirism and Geology of the Petroleum Deposits of Roumania), by A. de Boulard. *Rev. Petrol.* (Paris), No. 642 (August 3, 1935), pp. 983–84.

* "Recent Roumanian Work Has Developed Little of Great Importance, and Activity Down," by F. W. Penny. *Oil Weekly* (Houston, Texas), Vol. 78, No 12 (September 2, 1935), p. 36, 1 map.

RUSSIA

* "Soviet Oil Resources," by J. Wegrin. *World Petrol.* (New York), Vol. 6, No. 9 (September, 1935), pp. 546–50, 1 map. Statement of I. Gubkin's estimate of Soviet oil resources.

TEXAS

* "Southwest Texas District Enhanced by New Pools, Deeper Pays, Extensions," by C. A. Warner. *Oil and Gas Jour.* (August 29, 1935), pp. 57, 60, 63, 64, 67, 9 figs., and special insert map showing location of fields and pipe lines.

ASSOCIATION DIVISION OF PALEONTOLOGY AND MINERALOGY

* *Journal of Paleontology* (Fort Worth, Texas), Vol. 9, No. 6 (September, 1935)

"Cephalopods from the Upper Cretaceous of Kansas," by A. L. Morrow

"Ostracoda from the Amsden Formation of Wyoming," by Philip S. Morey

"Micropaleontology and Stratigraphy of the Lower Pennsylvanian of Central Missouri," by Willard F. Bailey

"Adolescent Development of *Ditomopyge*," by J. Marvin Weller

"Fresh-Water Invertebrates from the Morrison (Jurassic?) of Wyoming," by C. C. Branson

"*Rotalia viennoti*, an Important Foraminiferal Species from Asia Minor and Western Asia," by D. A. Greig

"Larger Foraminifera of Northern Santa Clara Province, Cuba," by M. G. Rutten

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EFFECT OF ANISOTROPY ON APPARENT RESISTIVITY CURVES

CORRECTION

In the article, "Effect of Anisotropy on Apparent Resistivity Curves," by Sylvain J. Pirson, in the January *Bulletin*, the following corrections should be made:

Page 44, line 11: $\xi', \eta' \zeta'$ should be ξ, η, ζ.

Page 51, line 2: "multiplied" should be *divided*.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 19, NO. 10 (OCTOBER, 1935), P. 1567

THE ASSOCIATION ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The executive committee has approved for publication the names of the following candidates for membership in the Association. This does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it promptly to J. P. D. Hull, business manager, Box 1852, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each nominee.)

FOR ACTIVE MEMBERSHIP

Alton C. Allen, Fort Worth, Tex.
Dugald Gordon, A. L. Selig, Sidney A. Judson
Barney Fisher, Dallas, Tex.
Ellis W. Shuler, J. C. Karcher, Eugene McDermott

FOR ASSOCIATE MEMBERSHIP

George W. Baughman, Wichita, Kan.
W. A. Ver Wiebe, John F. Kinkel, Rycroft G. Moss
John Franklin Bricker, Cisco, Tex.
T. F. Petty, W. K. Esgen, P. G. Russell
Thomas Frances Hill, Tyler, Tex.
Frederic H. Lahee, Wallace Ralston, Francis E. Heath

FOR TRANSFER TO ACTIVE MEMBERSHIP

William Boyd Ferguson, Brenham, Tex.
Frederic H. Lahee, J. A. Waters, L. W. Storm
Sam Zimerman, Big Rapids, Mich.
Bela Hubbard, Dave P. Carlton, J. E. LaRue

PACIFIC SECTION ANNUAL MEETING, NOVEMBER 7-8, 1935

The twelfth annual meeting of the Pacific Section of the Association will be held at Los Angeles, November 7 and 8. Chester Cassel is chairman of the program committee and H. K. Armstrong is chairman of the entertainment committee. Technical papers on many current problems will be presented and discussed. A. I. Levorsen, president of the Association, will address the meeting. Harold W. Hoots, 1113 Union Oil Building, is president of the Section. The Southern California-Stanford football game will be played on Saturday, November 9.

AT HOME AND ABROAD

CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION

Dwight H. Thornburg has moved from Newhall, California, to 343 West Fourteenth Street, Casper, Wyoming.

Roy R. Morse, of the Shell Oil Company, has moved from Los Angeles, California, to the Shell Building, Houston, Texas.

Wallace Lee is geologist with the United States Geological Survey, Washington, D. C.

Ed. Shakely, of the Shell Petroleum Corporation, has moved from McPherson, Kansas, to Tulsa, Oklahoma.

Joseph P. Connolly, professor of mineralogy, petrography, and economic geology, has been appointed president of the South Dakota School of Mines, succeeding the late C. C. O'Harra.

Kenneth E. Caster is carrying on paleontological and stratigraphic work on the Upper Devonian. Recently an instructor at Cornell University, he is affiliated with the Paleontological Research Institution at Ithaca, New York.

A. A. Olsson, of the International Oil Company, and president of the Paleontological Research Institution at Ithaca, New York, talked before the Institution on the "Structure of the Northern Andes."

The Pennsylvania Academy of Science held its summer meeting at East Stroudsburg, August 9 and 10. E. M. Gress, State botanist, led a trip on the 9th, and Bradford Willard, of the State Geologic Survey, led a trip on the 10th, studying the fossiliferous Devonian localities.

Charles Laurence Baker, formerly chief geologist of the Rio Bravo Oil Company, and recently geologist in the University of Texas Bureau of Economic Geology, has been appointed head of the department of geology at the Agricultural and Mechanical College of Texas, College Station, Texas.

W. A. J. M. van Waterschoot van der Gracht, of the Netherlands Mining Service, has moved his office and the offices of the Service from Maastricht to 95 Akerstraat, Heerlen, Holland.

Basil B. Zavoico has moved to Houston, Texas, where he is opening an office in the Gulf Building. He will continue doing consulting work in petroleum geology and economics and will be in charge of editing and advertising in the Mid-Continent area for Russell Palmer Publications, including *World Petroleum*, *World Petroleum Directory*, and *Petroleum World*.

A. Irving Levorsen, president of the Association, is now a resident of Tulsa, Oklahoma. His address is 221 Woodward Boulevard.